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COST-EFFECTIVE DESIGN OF WASTEWATER TREATMENT FACILITIES BASED ON FIELD DERIVED PARAMETERS

ST. LOUIS METROPOLITAN SEWER DISTRICT

PREPARED FOR
ENVIRONMENTAL PROTECTION AGENCY

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Extensive field investigations were conducted at two large primary treatment plants to define the variability of flow, primary effluent pollutants, and waste solids production. These data plus that collected during a pure oxygen pilot plant investigation were utilized in specially developed cost-effective computer programs for activated sludge treatment and waste solids handling to solve for the optimum design configuration as a function of the design reliability.

A surprisingly high degree of design reliability was found to be justified in municipal wastewater treatment with the traditional means of operational flexibility (oxygen supply, return sludge, solids storage, etc.) exerting little impact on the total annual cost of the facility.

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By

Metropolitan St. Louis Sewer District
St. Louis, Missouri 63125

and

Havens and Emerson, Ltd.
Cleveland, Ohio

Grant No. 11060 GVT
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NATIONAL ENVIRONMENTAL RESEARCH CENTER
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CINCINNATI, OHIO 45268

REVIEW NOTICE

The National Environmental Research Center -- Cincinnati has reviewed this report and approved its publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment -- air, water, and land. The National Environmental Research Centers provide this multi-disciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and

- a search for ways to prevent contamination and to recycle valuable resources.

This report describes the engineering parameters that must be considered to provide a reliable process design and, in turn, cost-effective wastewater treatment before discharge to the environment.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

Field investigations were conducted at two major primary treatment water pollution control facilities in preparation for design of secondary treatment facilities. These plants, although physically similar and processing similar quantities of wastewater, have widely different wastewater qualities and main interceptor systems. These two plants were investigated over an eight month period, using four hour grab and twenty-four hour composite samples, to identify average week and day hydraulic and primary effluent pollutant mass profiles using specially developed computer programs. These programs gave the percent less than occurrence of hydraulic and pollutant mass factors, and the consecutive day generation of waste primary and secondary solids, against average day values. In addition, a pure oxygen pilot plant was operated for 21 weeks at one of the plants to investigate secondary treatment criteria.

The results of these plant investigations and results of the pilot plant study were utilized with two cost-effective computer programs (activated sludge and waste activated sludge) to determine the influence of wastewater characteristics on the point of optimum design as a function of the design reliability. The influence of planned designed reliability upon operational flexibility and system performance dependability are discussed in light of current design standards and criteria.

This report was submitted in fulfillment of Grant No. 11060 GVT under the sponsorship of the U.S. Environmental Protection Agency.

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SECTION I

CONCLUSIONS

The two physically similar Metropolitan St. Louis Sewer District primary wastewater treatment plants characterize the extremes encountered in municipal wastewater treatment. Bissell Point, with a submerged interceptor subject to weekly pumpdowns, receives a strong wastewater dominated by industrial discharges. Lemay, on the other hand, has a conventional gravity interceptor system (little or no hydraulic buffering) and a highly diluted wastewater.

Whereas, Lemay had no significant day-of-the-week variation in wastewater flow or quality, industrial waste discharges at Bissell Point exerted obvious changes which were exaggerated with the Wednesday pumpdown of the submerged interceptor. Flow, COD, and suspended solids mass, however, all showed a greater absolute variation from average day values at Lemay. The latter observation was attributed to the stabilizing influence derived from Bissell Point's submerged interceptor, "relative" freedom from chronic infiltrated conditions and continuous receipt of strong, highly concentrated industrial wastes.

Consecutive day generation factors for waste primary and secondary solids were noticeably higher at Bissell Point than at Lemay due to the presence of industrial wastes and operation of the submerged interceptor. The primary sedimentation system provides an obvious benefit in dampening the extremes of waste secondary solids production at both plants.

Detailed cost/effective mathematical models were developed to describe pure oxygen activated sludge treatment (oxygenation reactor, oxygen production, sedimentation and return sludge) and disposal of the resultant waste activated sludge (gravity thickening, aerobic digestion (storage), vacuum filtration dewatering, and incineration). Input parameters were established from the plant and pure-oxygen pilot plant investigations. It was found that the optimum point of design reliability for both plants was 97.6 percent. Increasing reliabilities resulted in a gradual decline of the benefit/cost ratio to about 90 percent of optimum at 99.91 percent reliability. The traditional operating tools (oxygen supply and return sludge capabilities) were found to be relatively insensitive contributors to the final optimized cost of the pure oxygen activated sludge system. Optimum secondary treatment criteria (F/M ratio, oxygen supply, sedimentation overflow rate, and return sludge) were found to be similar to those recommended in conventional design criteria with the only significant deviation found in the return sludge capability due to the superior densification characteristics exhibited by the pure oxygen sludges.

Gravity thickening of waste activated sludge was found to be cost effective under all conditions investigated. An aerobic digester volume equivalent to one average maximum day storage had a benefit or liability in the order of five percent or less, which is assumed

negligible. The optimum design CRT (cell residence time) was found in a range of 4 to 7 days CRT. Design of the waste solids handling system for a CRT of 4 days, with an activated sludge reactor system design CRT of 7 days results in an approximate 3.5 to 5.5 percent increase of the facility's total annual costs. This cost increase is clearly justified when the plant's increased design reliability and operational flexibility are considered.

SECTION II

RECOMMENDATIONS

It is recommended that municipal wastewater treatment facilities be designed in light of integrated system performance and the cost effectiveness of obtaining increasing degrees of reliability. At minimum, it is recommended that all systems be designed for rationally defined boundary conditions and peaking factors. A recommended boundary condition for an activated sludge system would be on the order of ±25 to 33 percent of the nominal cell residence time. The main treatment system (reactor, final clarifier, return sludge, oxygen supply) should be designed for the high CRT and the waste solids handling and disposal system should be designed for the low CRT. Appropriate peaking factors should be applied to these boundary conditions.

SECTION III

INTRODUCTION

BACKGROUND

Design and performance criteria for municipal wastewater treatment facilities are traditionally reported in terms of average day conditions. This average operating day, however, is not a typical occurrence and extremes are more critical in operation than the nominal conditions.

In the design of any processing sequence, the engineer incorporates some excess capacity to accommodate swings in the quantity and quality of feed material (and/or equipment outage) to assure continous processing and end-product uniformity. Design, therefore, becomes one of extremes or the application of peaking factors over average day conditions. The magnitude of these peaking factors as applied in design determines the degree of design reliability. Ultimately, the degree of design reliability establishes the magnitude of performance dependability.

Traditionally, design reliability of activated sludge systems has depended upon oxygen supply and return sludge capacity. Performance dependability includes these parameters plus the installed capability for solids-liquid separation and waste solids handling and disposal. Every designer, design organization, and regulatory authority has guidelines based on experience that govern the selection of any given peaking factor or magnitude of excess capacity. These guidelines may be established from an extensive examination of existing or similar plant records, sophisticated probability and risk computations, or may be completely arbitrary.

Current Federal Guidelines state that all water pollution control facilities should be planned and designed so as to provide for maximum reliability at all times; resulting in a facility which is virtually "Fail-Safe"[1]. Reliability in the 1970 Guidelines was largely restricted to physical considerations, i.e., satisfactory operation during power failures, flooding, peak loads, equipment failures, and maintenance shutdowns, with a minimum of primary treatment at all times. By 1973, the general 1970 process performance descriptive terms (satisfactory operation and minimum of primary treatment) had been increased to the following U.S. EPA Standard for the final effluent from all publicly owned wastewater treatment plants by July, 1977[2]:

Maximum monthly average BOD_5 and SS = 30 mg/l

Maximum weekly average BOD_5 and SS = 45 mg/l

These effluent standards, in turn, establish a process performance reliability that is desired by the Federal Government. The probability of this performance reliability is not defined and the question of cost to benefit to risk is not explored. Although the performance reliability inherent with the proposed Federal Standards has not been defined, the cost increases associated with different degrees of design reliability

can be developed for any given plant. In preparing a process design, the engineer expects a range of variation in operating parameters within which he selects a set of design criteria for sizing of treatment units and selection of equipment. The ability of the plant to perform satisfactorily over this range of operating conditions depends on this selection of design criteria; the more conservative his selection, the more reliable is the plant in consistently meeting the operating goals throughout the full operating range of variables.

Thus, design reliability, for the purposes of this report refers to the extent to which the design covers the full range of peaking factors expected; the term does not refer to provision of stand-by equipment or other measures of redundancy.

The Metropolitan St. Louis Sewer District is currently expanding its two major primary treatment facilities for secondary treatment equivalency. These plants, both processing in the order of 100 million gallons per day (mgd), characterize the extremes encountered in municipal wastewater treatment. Bissell Point, with a submerged interceptor subject to weekly pumpdowns, receives a strong wastewater dominated by industrial discharges. Lemay, on the other hand, has a conventional interceptor system (little or no hydraulic buffering) and a highly diluted wastewater. Both plants are less than five years old and provide vacuum filtration and incinerator for primary sludge disposal with the residual ash transported to storage lagoons. In 1971 and 1972, a variety of special plant, pilot plant, and laboratory investigations were conducted to provide guidance and design information to the District's consulting engineers. Where applicable, these investigations are described in subsequent sections of this report. The data collected during these investigations is used herein to define the cost and design impact of different degrees of design reliability for each plant with their uniquely different wastewater characteristics.

OVERALL OBJECTIVES

The overall objective of this investigation was to examine the cost of secondary wastewater treatment as a function of different design reliabilities and the widely different wastewater qualities encountered at the two St. Louis plants. To meet this overall investigative objective, the following program goals were established:

Plant Investigations:

Establish and characterize daily diurnal flow and pollutant mass variation, probability of occurrence of any flow or pollutant mass variation against the average occurrence, and consecutive day generation factors for waste primary and secondary solids. Develop usable computer program for these determinations.

Pilot Plant Investigations:

Determine ammenability of primary effluent stabilization by a representative biochemical process.

Characterize the performance of this treatment technique in terms of design parameters.

Secondary Wastewater Treatment Costs Versus Design Reliability:

Develop cost effective computer programs for secondary treatment and waste solids disposal. Establish optimum point of design reliability versus treatment expenditure.

ANALYTICAL PROCEDURES

All analytical procedures were performed in accordance with Standard Methods[3] with the exception of the COD reflux time where 30 minutes was found to fully quantify wastewater COD levels. Soluble analyses were performed on the resultant filtrate derived from passing the sample through glass fiber filters (Reeve Angel Glass Fiber Filters, Grade 934AH), which were utilized for suspended solids measurements.

SECTION IV

PLANT INVESTIGATIONS

OBJECTIVES

Investigative activities at the two water pollution control facilities were oriented to determine the following:

> Daily diurnal flow and pollutant mass variation; probability of occurrence of any flow or pollutant mass variation against the average occurrence; and consecutive day generation of waste primary and secondary solids.

The above are utilized in design to identify problem days in terms of plant operation or wastewater quality, and to establish peaking factors for hydraulic, pollutant mass, and waste solids quantities. Although the results are specific to the two Metropolitan St. Louis treatment plants, the ratios obtained can be utilized as a guide in the design of other facilities which experience similar conditions and flows where similar rigorous investigative programs cannot be conducted.

PROCEDURES AND TECHNIQUES

As mentioned previously, both the Bissell Point and Lemay Treatment Plants are to be expanded to provide secondary treatment. The diurnal variation of each plant's primary effluent was evaluated over an eight month period to aid in the development of design peaking factors. During this time, flows were recorded and primary effluent samples were collected every four hours (0030, 0430, 0830, 1230, 1630 and 2030). The samples were immediately refrigerated and analyzed daily for pH, BOD_5, COD and suspended solids. Other analyses (ammonia, total and soluble TKN and phosphorus, and soluble BOD_5 and COD) were also performed periodically during the survey period. These analyses plus those obtained from the plant's normal 24 hour, flow proportional composites constituted the raw data.

The raw data was then introduced into a specifically developed computer program using the SBC Call/370 System with PL/1 language. This program, DFC (Diurnal-Frequency-Consecutive), is listed in Appendix A. The subprograms are described as follows:

Diurnal

In the initial subprogram, daily data from the four hour sampling program are used to describe a hypothetical week or day for any given month for selected parameters. The parameters may be single entries (such as flow or concentration) or mass values (flow times concentration times 8.34). With multiple months, a final readout is obtained which describes the hypothetical week and day for all the data.

Frequency

In this subprogram, raw data (either flow or mass) from the four hour sampling program is grouped on a "percent less than occurrence" for each month. This frequency or probability of occurrence plot contains the following data points for a four hour sampling frequency:

	Percent Less Than	
	Peak	Minimum
Average Daily Four Hour Peak or Minimum / Average Day	83.3	16.7
Average Weekly Four Hour Peak or Minimum / Average Day	97.6	2.4
Average Monthly Four Hour Peak or Minimum / Average Day	99.44	0.56

Consecutive

The final subprogram identifies the maximum and minimum factors for waste solids mass generation for 1, 3, 5 and 7 consecutive days in comparison to the average waste solids on a monthly basis. Primary sludge mass is determined by multiplying the daily plant influent flow times the difference between the influent and primary effluent suspended solids times a constant. Waste secondary sludge mass is assumed as proportional to the organic mass of the primary effluent, i.e., daily plant influent flow times the daily primary effluent COD times a constant. All 24 hour daily samples are flow proportional.

RESULTS AND DISCUSSION

Background Performance

Average wastewater quality and plant performance for the two MSD primary treatment facilities during their respective eight month investigative period are reported in Table 1. Both plants are operating in the range of 50 to 67 percent of their design capacity. Typically, Bissell Point maintains five-eighths of its primary sedimentation tankage in service, whereas, Lemay uses seven-eighths of its primary system. The industrial waste influence at Bissell Point and continuous dilution influence at Lemay is readily observable on a brief examination of the influent wastewater quality at both facilities. Influent wastewater quality for the reported parameters at Bissell Point is on the order of two to three times greater than experienced at Lemay. Although operating at dissimilar surface overflow rates, both plants achieve similar removal efficiencies of influent suspended solids. Undoubtedly, Bissell Point's high removal efficiencies are in part due to the high applied influent suspended solids concentration. Lemay's efficiencies, on the other hand, are probably assisted by the low surface overflow rate.

TABLE 1. AVERAGE EIGHT MONTHS OF PLANT PERFORMANCE*

PLANT:	BISSELL POINT	LEMAY
Investigative Period	March through October, 1972	February through September, 1972
Primary Sedimentation Surface Overflow Rate, gpd/sf	880	650
Flow, mgd	118	98
COD		
Influent, mg/l	825	261
Effluent, mg/l	465	175
Effluent, tons/day	230	72
Percent Removal	44	33
BOD_5		
Influent, mg/l	264	123
Effluent, mg/l	214	89
Effluent, tons/day	105	36
Percent Removal	19	28
Suspended Solids		
Influent, mg/l	352	182
Effluent, mg/l	128	62
Effluent, tons/day	63	25
Effluent, % Volatile	73	57
Percent Removal	64	66

*Average Results of Daily Samples

The wide difference between COD and BOD_5 removal efficiencies at Bissell Point indicates that the organic fraction of the removed suspended solids is not readily biodegradable as measured by conventional BOD determinations.

The preceding briefly describes the performance and wastewater quality encountered at the two MSD plants. The following describes results of the data collection, reduction, and interpretation of each eight month investigative period.

Diurnal Flow Variation

Figures 1 and 2 present the diurnal flow variation for a hypothetical week and day at the Bissell Point and Lemay Treatment Plants. The hypothetical week plot contains the average monthly maximum, average, and average monthly minimum for the day and hour indicated. The hypothetical day plot (midnight to midnight) averages the maximum, average, and minimum values of the hypothetical week at each appropriate hour.

Figure 1, the diurnal flow variation for Bissell Point, illustrates a consistent weekly hydraulic pattern: low Sunday flows which increase to a peak Wednesday flow (interceptor pumpdown day) with a subsequent decline to a minimum weekend flow. The obvious flow differences between weekday and weekend measurements are representative of weekday industrial activity. Excluding pumpdown day activities, flow minima and maxima are usually experienced in the early morning and afternoon hours, respectively. Hydraulically, the critical design day at Bissell Point would be the Wednesday pumpdown day.

Diurnal flow characteristics at Lemay, Figure 2, do not show a large weekday to weekend variation. Flow maxima and minima occur at the same time as at Bissell Point, but exhibit a much greater plateau effect. Comparing the envelopes described by the maximum and minimum, a much greater variation can be seen at Lemay than at Bissell Point. This variation, to a large degree, can be attributed to Lemay's greater susceptibility to storm flows. Bissell Point's submerged interceptor, on the other hand, can be expected to dampen daily diurnal swings of wastewater flow and may lose some stormwater through upstream regulating stations.

Diurnal Pollutant Mass Variation

Figures 3 and 4 describe the diurnal primary effluent pollutant (COD and SS) mass flow variation for Bissell Point and Lemay. The hypothetical week and day plots were obtained in a similar manner as previously described with the hydraulic flows.

The Bissell Point data, Figure 3, shows a much greater variation with the organic (COD) than the suspended solids. This is due to the soluble phase organic pollutants. Daily primary effluent pollutant peaks generally lag peak flows due to the flow-through time of the primary sedimentation system. Daily changes between maximum and

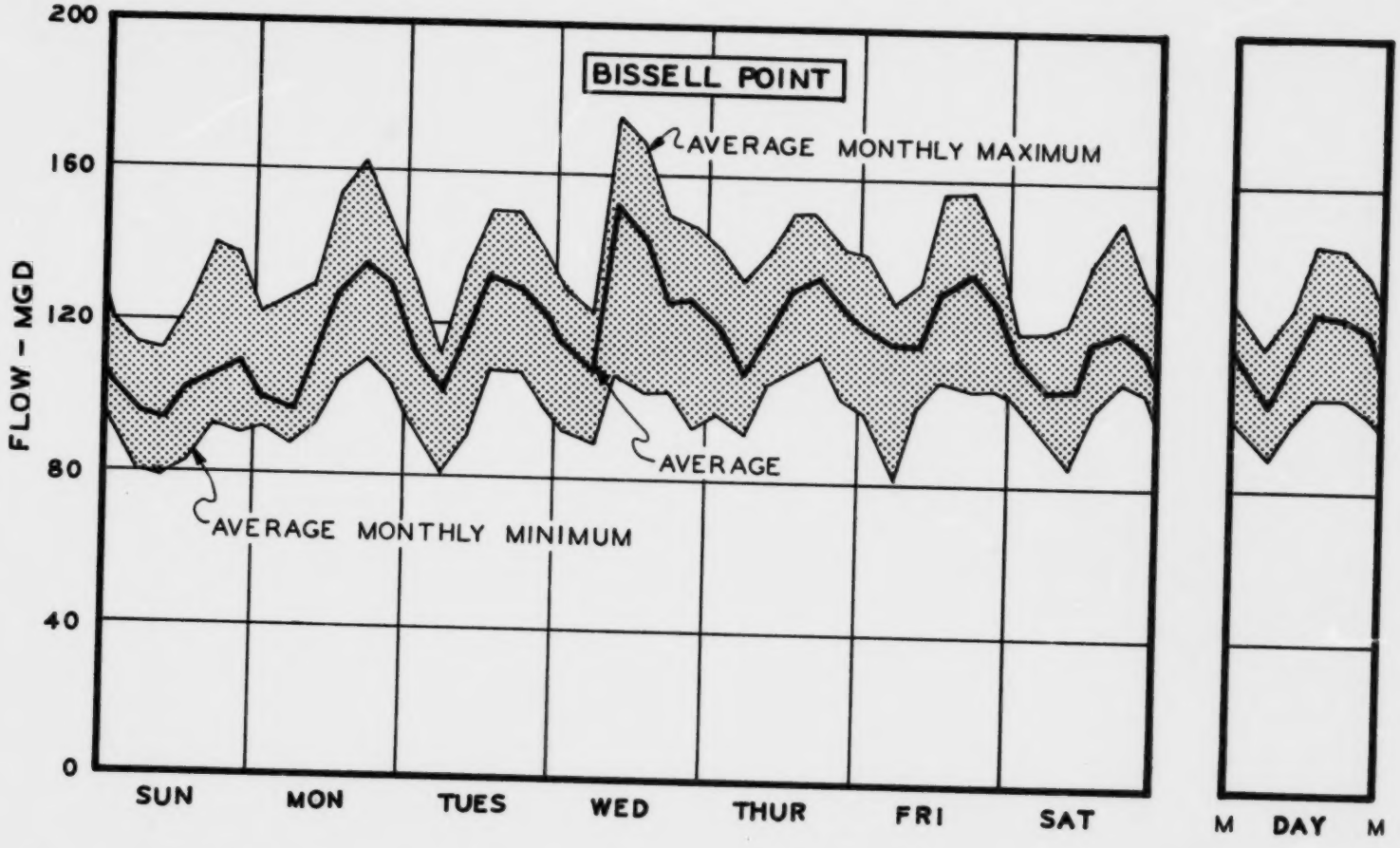


FIGURE I. DIURNAL FLOW VARIATION : HYPOTHETICAL WEEK AND DAY

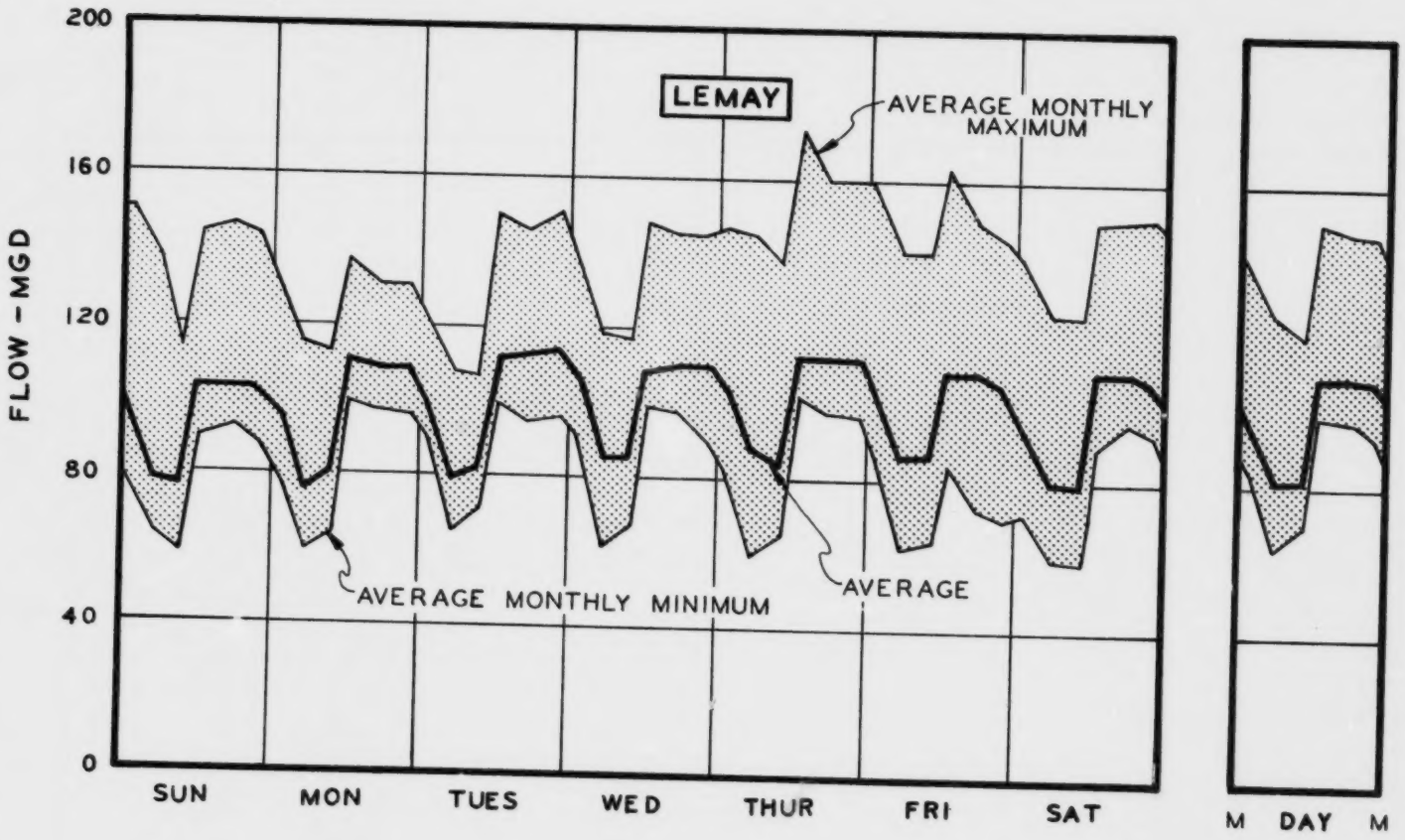


FIGURE 2. DIURNAL FLOW VARIATION: HYPOTHETICAL WEEK AND DAY

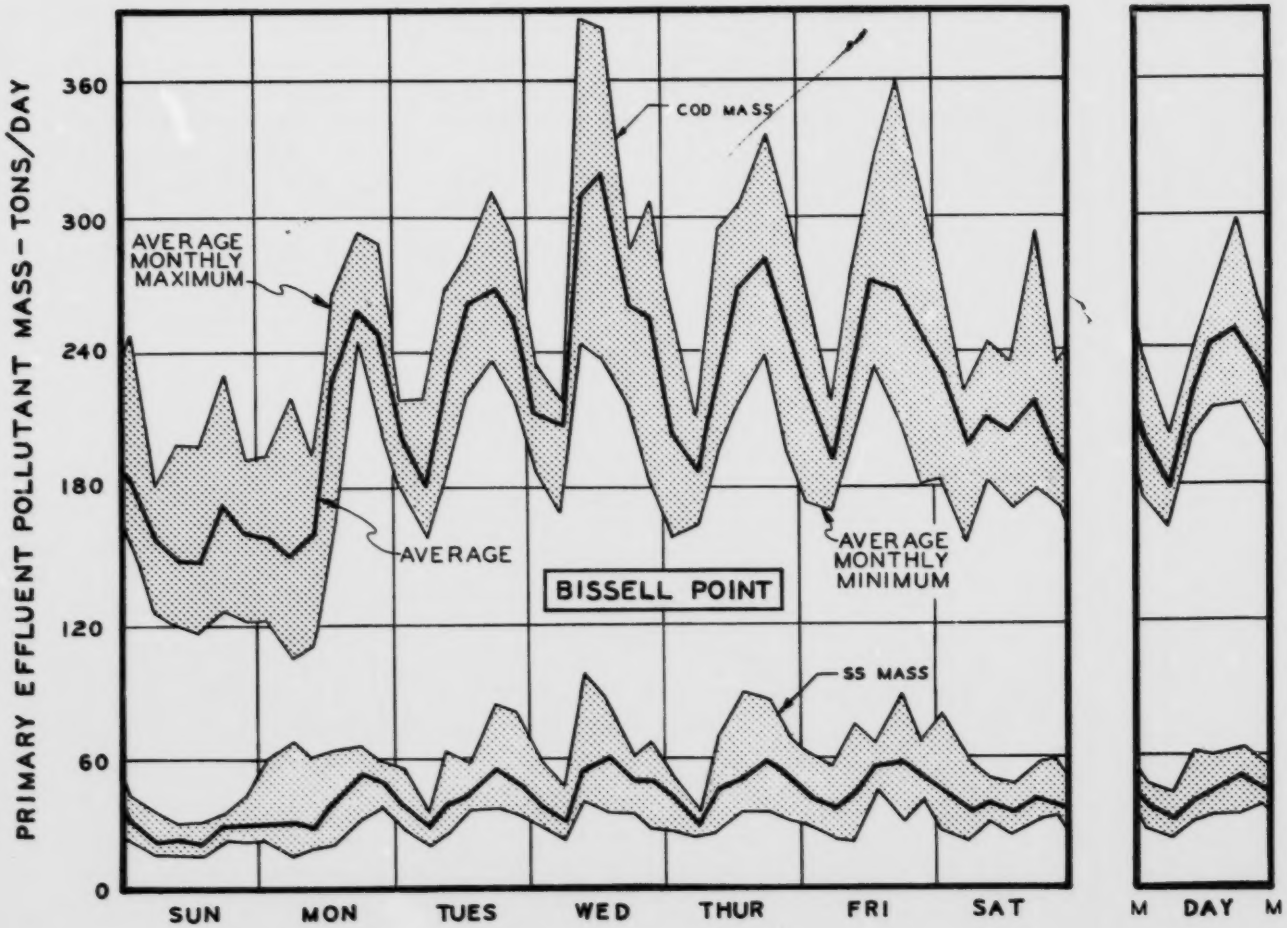


FIGURE 3. DIURNAL PRIMARY EFFLUENT POLLUTANT MASS FLOW VARIATION

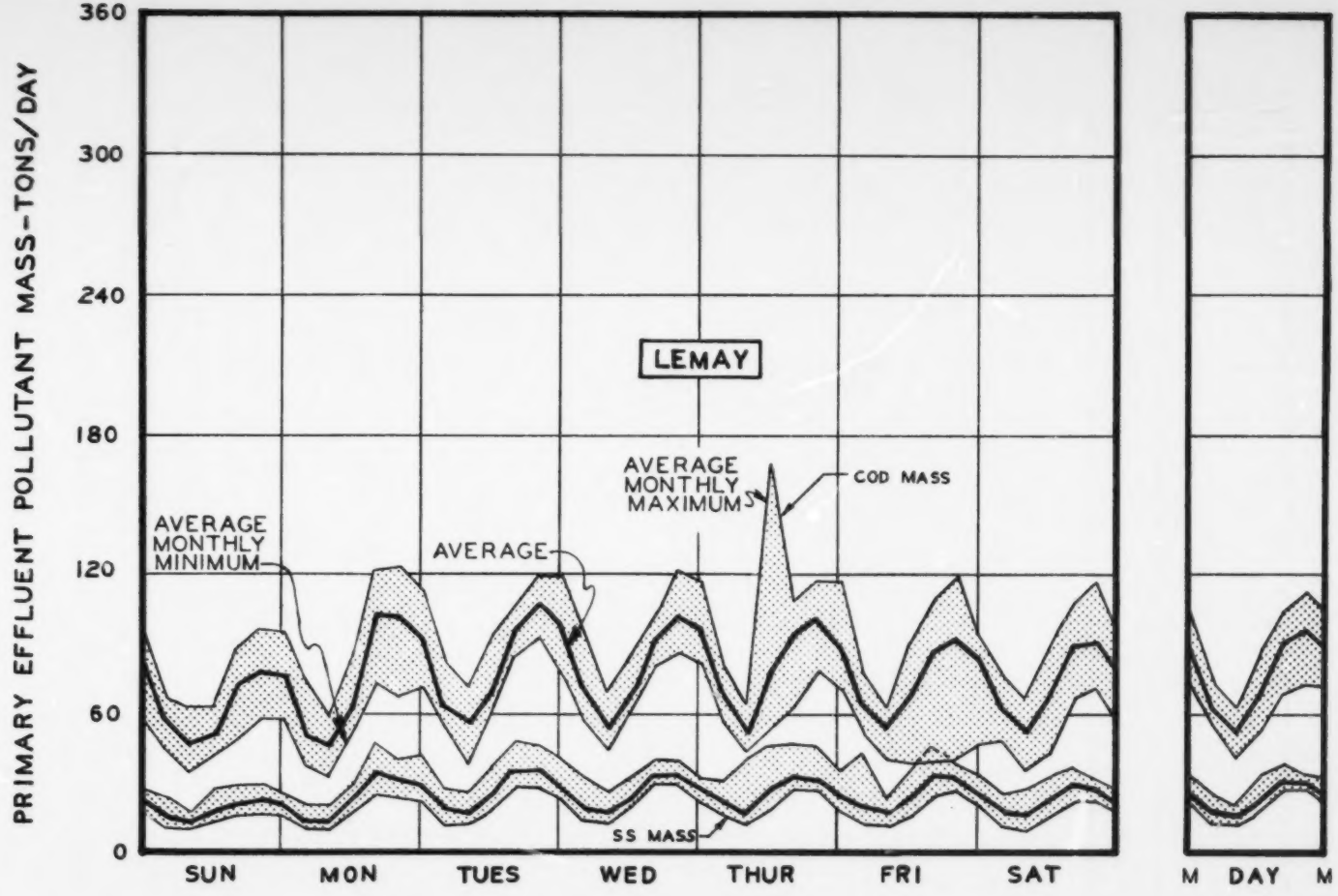


FIGURE 4. DIURNAL PRIMARY EFFLUENT POLLUTANT MASS FLOW VARIATION

minimum values are quite pronounced. Differences between weekday and weekend pollutant mass flows are further exaggerated, indicating an increase in pollutant concentration coinciding with flow. Again, the critical design day occurs on Wednesday. An obvious means of minimizing the impact of the pumpdown day is to transfer this operation to a day when wastewater flows and characteristics are the lowest; this would be on Sunday.

The Lemay primary effluent mass flow variation, Figure 4, is much lower than that encountered at Bissell Point, due to the absence of pronounced industrial waste discharges. The lower Sunday pollutant mass flow values, however, may be indicative of lower weekend industrial activity. Again, as at Bissell Point, organic (COD) variation is much more pronounced than suspended solids, due to the soluble phase pollutants.

Frequency Distributions

Percent less than occurrence frequency distribution for flow, COD mass, and suspended solids mass are contained in Figures 5, 6 and 7 respectively. They were developed by plotting the output of frequency subprogram (Page 8). These plots show the average values for all eight months plus the extremes defined by the maximum and minimum months. Projections above or below the average monthly four hour peak or minimum to average four hour value (above 99.44% less than or below 0.56% less than) are indicated by a dashed average line and a change in the shading of the envelope.

The flow distribution for both plants is contained in Figure 5. It can be seen that the Lemay flow distribution is greater than found at Bissell Point. This is attributed to Lemay's chronic infiltration problem which becomes pronounced during periods of heavy runoff and the lower amount of storage capacity in the plant's main interceptor system. However, it should be noted that the deviation between the two plants does not become pronounced until an occurrence of 98 percent less than.

The difference between the two plants becomes even more exaggerated upon examining the percent less than occurrence of the COD and suspended solids primary effluent mass, Figures 6 and 7. Bissell Point's greater stability can be attributed to the influence of nearly continuous discharges of concentrated industrial wastes and "relative" freedom from chronic infiltration problems.

Consecutive Day Waste Solids Production

Figures 8 and 9 give the consecutive day production of waste primary and secondary sludge, respectively. As before, these plots give the average value for all eight months with the extremes defined by the maximum and minimum months.

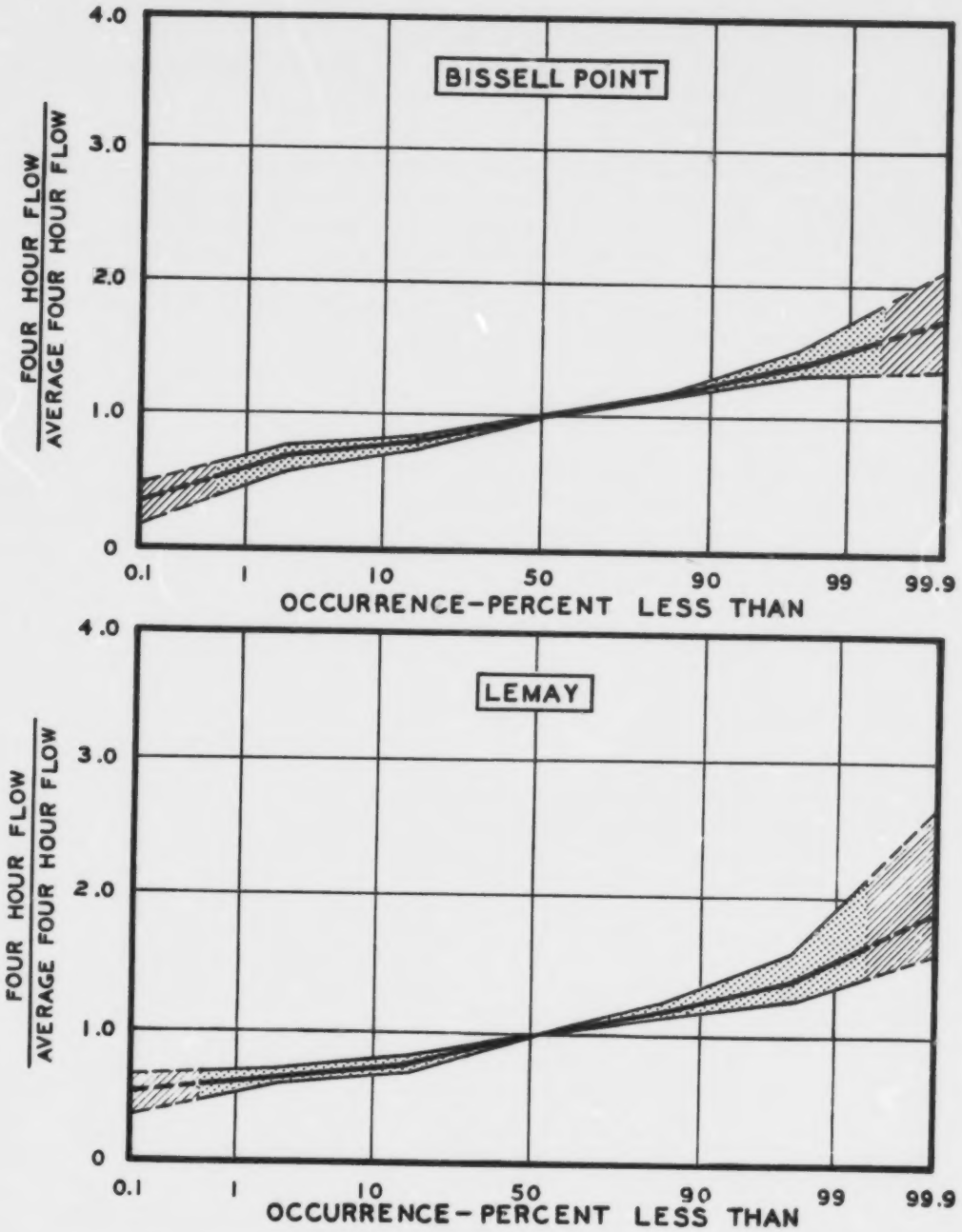


FIGURE 5. FOUR HOUR INTERVAL FLOW VARIATION

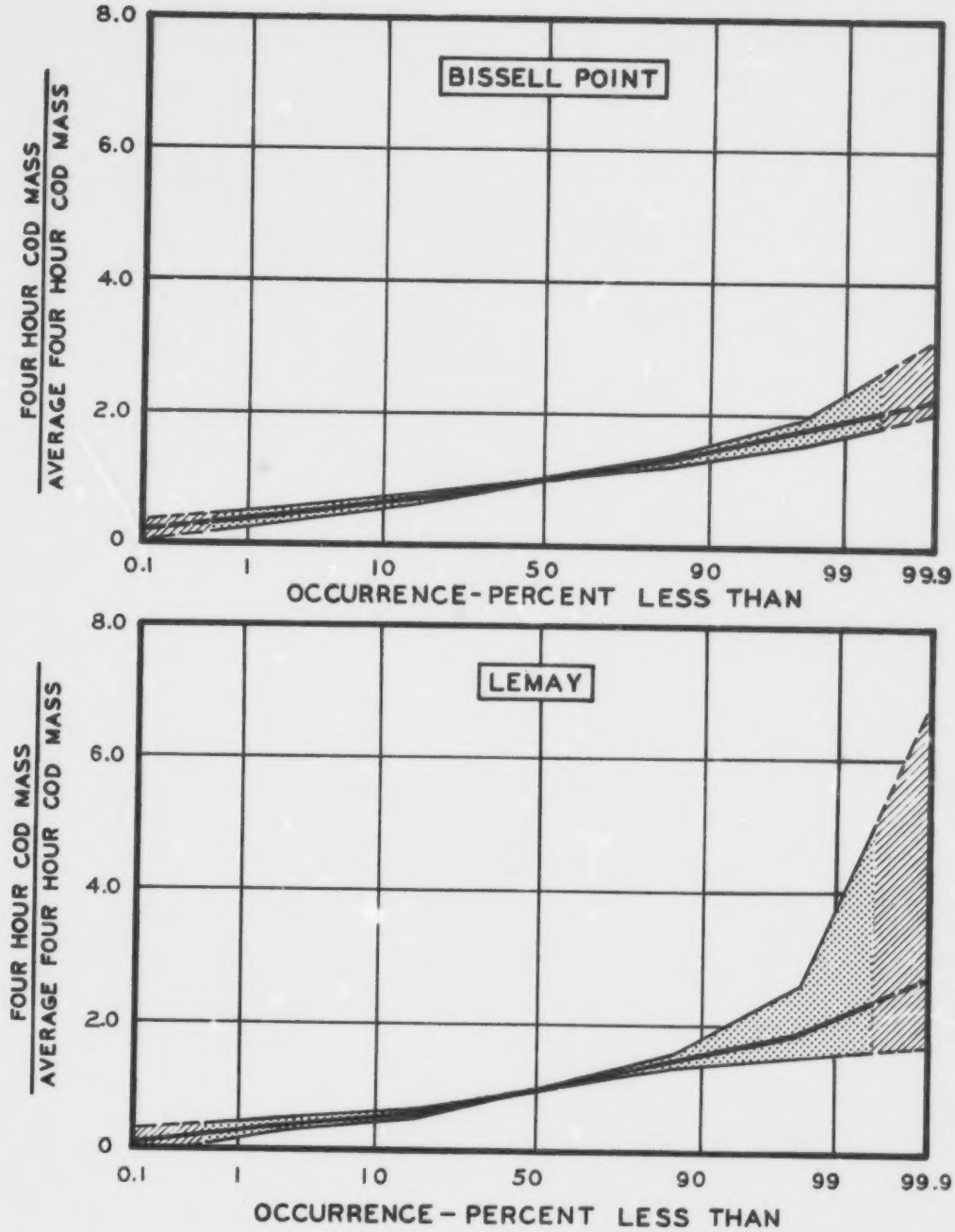


FIGURE 6. FOUR HOUR INTERVAL PRIMARY EFFLUENT COD MASS FLOW VARIATION

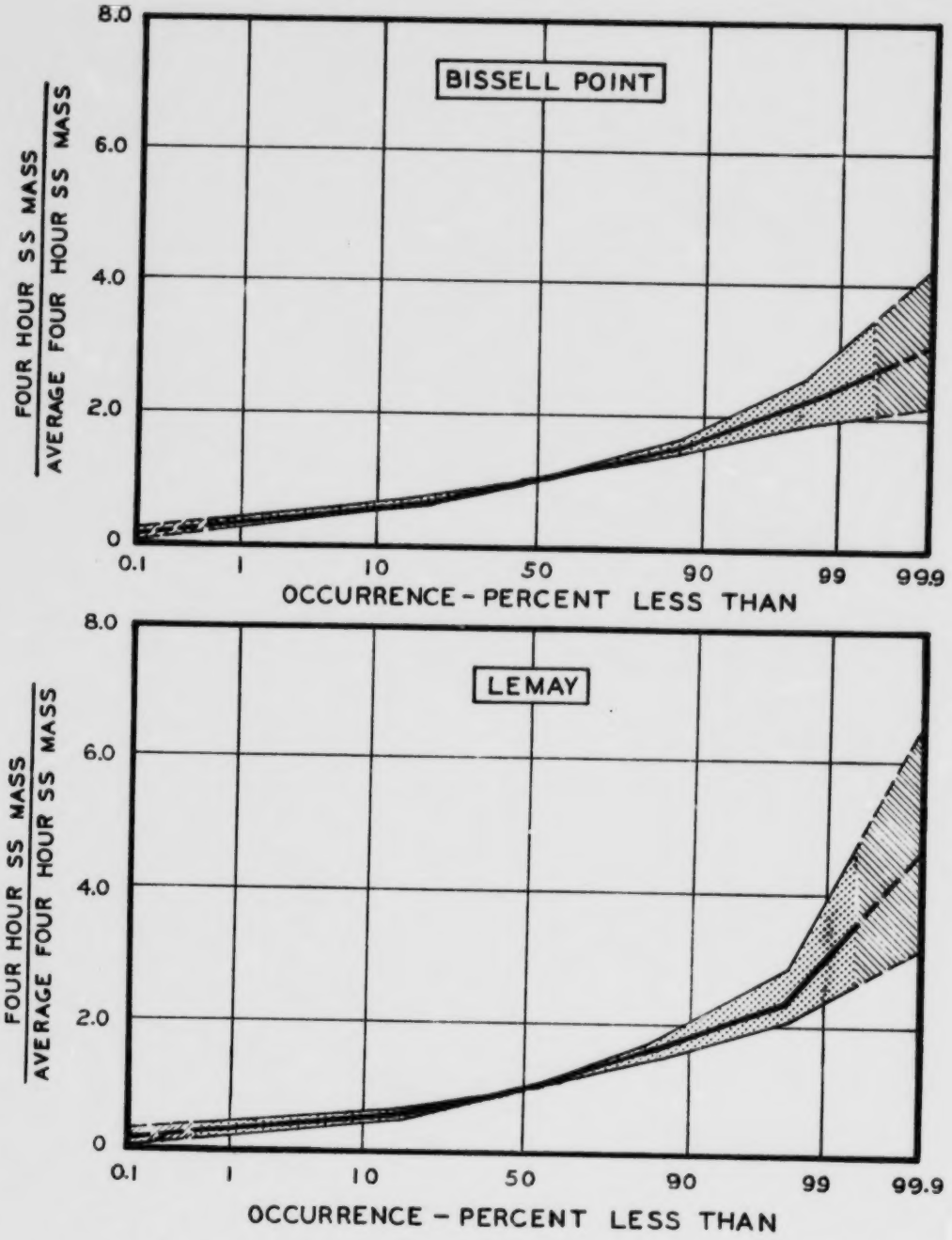


FIGURE 7. FOUR HOUR INTERVAL PRIMARY EFFLUENT SS MASS FLOW VARIATION

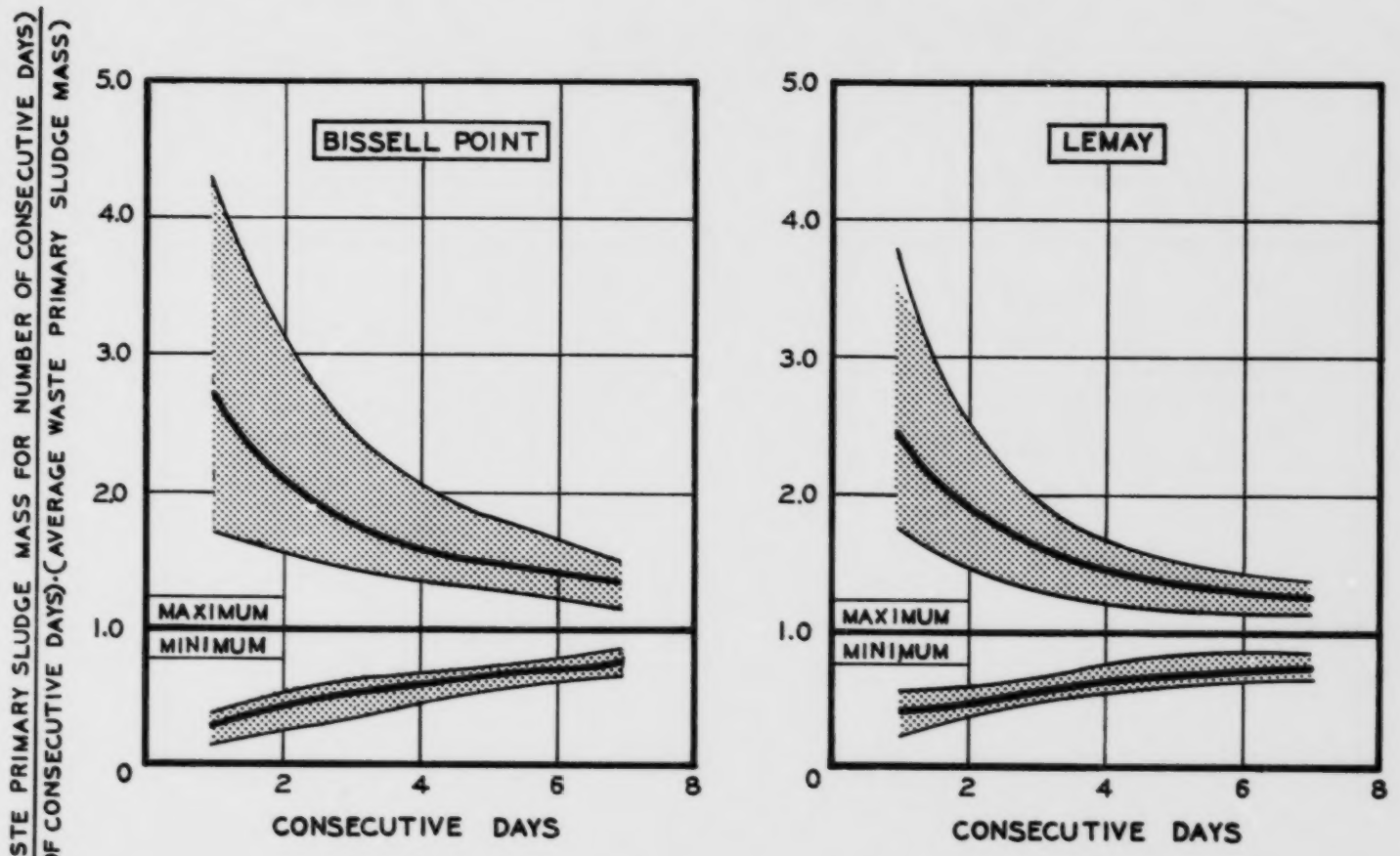


FIGURE 8. CONSECUTIVE DAY GENERATION OF WASTE PRIMARY SLUDGE: MAXIMUM AND MINIMUM FACTORS

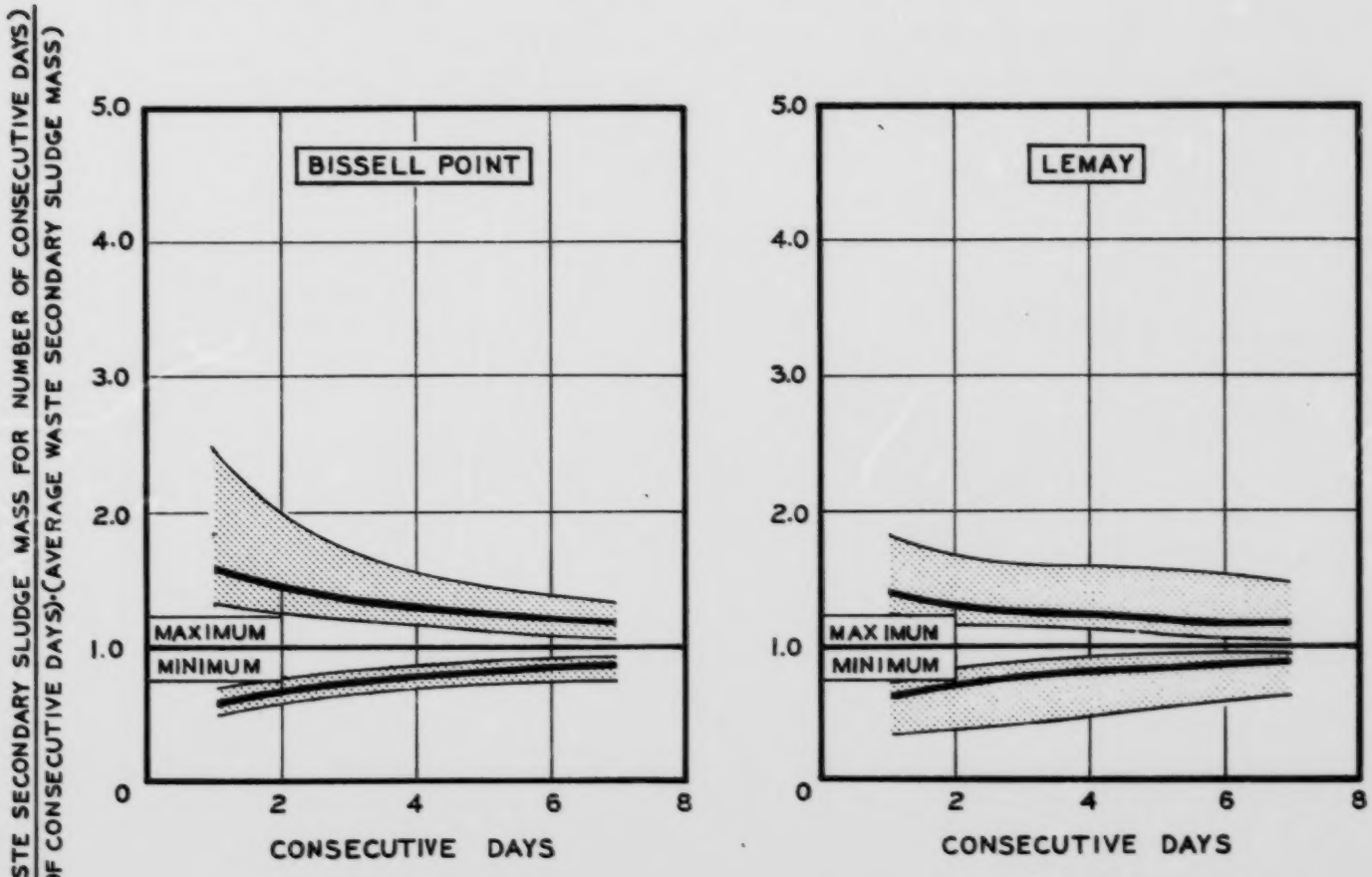


FIGURE 9. CONSECUTIVE DAY GENERATION OF WASTE SECONDARY SLUDGE: MAXIMUM AND MINIMUM FACTORS

As shown in Figure 8, maximum and minimum factors for consecutive day generation of waste primary solids are higher at Bissell Point than for Lemay. This is most likely due to the plant's industrial waste load plus the influence of the interceptor pumpdown day as any solids that may have settled in the interceptor are introduced into the plant.

The influence of both plants' primary sedimentation system upon waste secondary solids production (assumed proportional to the primary effluent COD) is demonstrated by comparing the consecutive generation of waste secondary solids in Figure 9 with the waste primary sludge generation factor in Figure 8. Again, Bissell Point's peaking factors for waste secondary sludge are higher than found at Lemay. This is attributed to its industrial waste and submerged interceptor weekly pumpdown characteristics.

CONCLUSIONS

The two Metropolitan St. Louis Sewer District primary wastewater treatment plants achieve similar suspended solids removal efficiencies treating flows on the order of 100 mgd of sewage flow. One, Bissell Point, has a heavy industrial waste load and a submerged plant interceptor which is pumped down weekly. The second, Lemay, has a normal gravity interceptor with a chronic infiltration problem. Raw wastewater strength (suspended solids, BOD_5, and COD) is two to three times higher at Bissell Point than at Lemay.

Diurnal flow and pollutant mass variations were measured at both facilities. Whereas, Lemay showed only a small variation between weekday and weekend influences, Bissell Point displayed an obvious variation, which was exaggerated on the Wednesday pumpdown of the interceptor.

Flow, COD mass, and suspended solids mass, all showed a greater variation (percent less-than occurrence) at the extremes for Lemay than for Bissell Point. This was attributed to the stability influence derived from Bissell Point's submerged interceptor, "relative" freedom from chronic infiltrated conditions, and the receipt of strong, highly concentrated industrial wastes.

The buffering capability of the primary sedimentation system in terms of waste secondary solids generation was readily demonstrated in calculating the consecutive day generation of waste primary and secondary solids. Bissell Point's consecutive day variability of waste solids generation was noticeably higher, which is attributed to the weekly pumpdown of the plant interceptor and the variable accumulation of deposited solids.

SECTION V

PILOT PLANT INVESTIGATION

OBJECTIVES

A variety of pilot plant and exploratory laboratory bench investigations were conducted with the Bissell Point wastewater. These investigations examined alternative means (bio-chemical oxidation and physical-chemical adsorption) of achieving secondary treatment equivalency. They ranged from an extensive twenty-one week investigation of pure oxygen activated sludge treatment to the determination of batch activated carbon adsorption isotherms. The overall objective of these studies was to determine the efficacy of each of the treatment techniques on the Bissell Point wastewater. The results of the pure oxygen pilot plant study are presented herein.

PURE OXYGEN ACTIVATED SLUDGE TREATMENT: PILOT PLANT

Description

A pure oxygen pilot plant (Union Carbide Unox System) receiving settled Bissell Point wastewater, was operated from June to December, 1971. The pilot plant contained a 1600 gallon reactor separated into four equal volume compartments with a nominal liquid depth of five feet. Its external final clarifier had a surface area of 38 square feet with a liquid depth of nine feet. Pure oxygen, provided in compressed gas cylinders, was introduced in the first stage of the reactor.

The operational program was divided into two phases. Phase I commenced June 22, 1971, with pilot plant seeding and the onset of 24 hour operation. Phase II began September 13, and lasted until project termination on December 14, 1971. Operation was provided by employees of the Metropoliton St. Louis Sewer District, according to the recommendations of either Union Carbide (Phase I) or the District's consultant, Havens and Emerson, Ltd. (Phase II). In Phase II, three extensive 10-11 day investigations were conducted at cell residence times (CRT) bracketing the potential operating mode of the biological system. These investigations were conducted following a conditioning period equal to 2.2 times the operating CRT under consideration. This conditioning period resulted in the achievement of ninety percent steady-state conditions prior to the onset of a run. Investigations were conducted at nearly constant flow rates to eliminate performance variables, i.e., effluent suspended solids, due to hydraulic changes.

Wastewater Quality

Primary effluent quality characteristics from July 1, 1971, through project completion are listed in Table 2. Organic (COD) and suspended solids concentrations are somewhat lower than measured during the

TABLE 2. BISSELL POINT PRIMARY EFFLUENT WASTEWATER QUALITY

(Unox Pilot Plant Feed)

A. PRIMARY EFFLUENT QUALITY - mg/l

Item	OBSERVATIONS PERCENT LESS THAN						
	Min.	10	20	50	80	90	Max.
BOD_5	72	153	176	214	248	266	357
COD	176	279	340	413	495	525	840
BOD_5/COD	0.13	0.38	0.44	0.52	0.58	0.61	0.89
SS	41	54	60	78	110	142	306
TKN	7	24	26	33	41	42	55
P	2.8	4.0	4.8	5.9	7.4	9.2	19.3

B. DAY OF THE WEEK COD VARIATION - mg/l

Day	Min.	10	20	50	80	90	Max.
Sunday	191	203	270	340	400	450	485
Monday	228	276	300	385	468	507	531
Tuesday	275	360	382	455	484	508	528
Wednesday	244	340	396	460	522	600	840
Thursday	290	340	357	424	505	535	550
Friday	212	260	335	450	526	538	680
Saturday	176	245	320	407	473	515	660

Average three consecutive day high/month = 525 mg/l COD

previously reported 1972 eight month plant investigation.

Investigative Results

Examination of the data obtained in Phase I showed a widely varying cell residence time or organic loading rate, on a week to week basis, indicating a lack of system equilibrium. Therefore, only the data collected in Phase II were utilized for detailed interpretation.

Table 3 describes the overall system performance of the Unox pilot plant for each investigative run. Accumulations of solids in the clarifier during Study No. 2 got out of control, and necessitated excessive wastage during the middle of the run; this resulted in an actual cell residence time of 3.8 days rather than the sought conditions of 6 days. Thus, for this run equilibrium conditions and sludge characteristics were established for a CRT of 6 days which were lost during the middle of the run. This resulted in sludge production characteristics from a younger CRT with probable main stream performance characteristics representative of the older CRT. As can be seen from Table 3, incorporation of secondary treatment via the Unox pilot plant system resulted in overall treatment efficiencies exceeding 85 percent for the major pollutional parameters (COD, BOD_5 and suspended solids). Older CRT's show a tendency to produce a lower soluble and total BOD_5/COD ratio in the final effluent. The lowest CRT of 3 days resulted in a noticeable increase of final effluent suspended solids.

Table 4 characterizes the system for each investigative period. Increases in the mixed liquor suspended solids (MLSS), return sludge rate (R), and final clarifier solids loading rate with increasing CRT are readily apparent. A reactor dissolved oxygen concentration of 8 mg/l or higher was consistently maintained throughout the study.

Table 5 summarizes the solids phase data collected during the Phase II investigations. The high accountability of the phosphorus mass balances indicates that a high confidence value can be placed upon the measured solids production. An oxygen-COD balance was also performed for each study period but failed to show a similar accountability. This was attributed to a combination of oxygen leaks and/or failure of the COD test to fully quantify the actual COD level. Mixed liquor, waste activated and final effluent solids are also characterized in the Table to illustrate the influence of operating conditions upon the solids streams. Contradictory to the expected, the volatility of the mixed liquor suspended solids increased with the CRT. This anomaly was attributed to a build-up of volatile nonbiodegradable cellular components, limited biodegradability of the influent volatile suspended solids, and the high soluble organic: inert suspended solids ration encountered in the Bissell Point primary effluent during and preceding the study period. The effluent suspended solids BOD_5/COD ratio, which progressively decreases with increasing CRT, also indicates a build-up of refractory volatile suspended organics. All mixed liquor and final effluent suspended solids characterizations, i.e., magnitude of BOD_5, COD, N and P contained in the particulate phase, were determined from soluble

TABLE 3. BISSELL POINT UNOX PILOT PLANT - OVERALL SYSTEM PERFORMANCE

PHASE II

Study		1			2			3		
Dates: From - Through		11/5 - 11/15			12/3 - 12/13			10/9 - 10/18		
Cell Residence Time - Days		3.0			6.0(3.8)			8.8		
Wastewater Quality		Infl*	PE	FE	Infl*	PE	FE	Infl*	PE	FE
COD	- mg/l	620	415	82	583	363	80	745	485	86
$COD_{soluble}$	- mg/l	-	-	56	-	-	57	-	-	65
BOD_5	- mg/l	211	246	14	217	193	16	300	239	8
$BOD_{5_{soluble}}$	- mg/l	-	-	7	-	-	8	-	-	3
TKN	- mg/l	(		)	-	31.0	17.9	-	37.2	23.9
$TKN_{soluble}$	- mg/l	(Incomplete)			-	-	15.4	-	-	21.0
NH_3-N	- mg/l	(Data		)	-	-	10.0	-	-	17.0
P	- mg/l	-	6.8	3.6	-	5.5	3.0	-	7.2	5.0
P_{sol}	- mg/l	-	-	3.0	-	-	2.5	-	-	4.2
SS	- mg/l	300	144	32	349	93	18	434	87	20
$\frac{VSS}{SS}$ x 100		68	64	76	56	67	72	62	71	76
pH		7.8	7.8	6.7	7.8	7.8	6.7	7.5	7.4	6.6
DO	- mg/l	-	-	4.0	-	-	2.6	-	-	4.0
BOD_5/COD		0.34	0.59	0.17	0.37	0.53	0.20	0.40	0.49	0.09
$(BOD_5/COD)_{soluble}$		-	-	0.12	-	-	0.13	-	-	0.05

Removal Efficiencies - %	Prim	Sec.	Ovrll	Prim	Sec.	Ovrll	Prim	Sec.	Ovrll
COD	33	80	87	38	78	87	35	82	88
BOD_5	17	94	93	11	92	93	20	96	97
TKN	-	-	-	-	42	-	-	36	-
P	-	47	-	-	45	-	-	30	-
SS	52	78	89	73	81	95	80	77	96

*Extracted from Bissell Point operating reports during study period.

TABLE 4. BISSELL POINT UNOX PILOT PLANT - SYSTEM CHARACTERIZATION

PHASE II

Study	1	2	3
Cell Residence Time - Days	3	6.0 (3.8)	8.8
HYDRAULIC SYSTEM			
Q - gpm	13.5	14.0	13.4
R - %	15	21	36
Detention Time (Q) - Hours	2.0	1.9	2.0
Detention Time (Q+R) - Hours	1.7	1.6	1.5
Clarifier Surface Overflow Rate (Q) - gpd/ft^2	510	530	510
Clarifier Solids Load - lb/ft^2 . day	28	32	48
REACTOR			
MLSS - mg/l	5,800	5,800	8,300
Volatile - %	70	72	80
SVI - ml/g	31	45	42
SVI (Stirred) - ml/g	25	35	30
DO - mg/l (average)	8.0	8.3	8.0
Temperature - °F	69	62	77
LOADINGS			
Lb. BOD_5/Lb. MLSS/day	0.54	0.42	0.35
Lb. COD/Lb. MLSS/day	0.87	0.78	0.70
Lb. BOD_5/Lb. MLVSS/day	0.74	0.58	0.43
Lb. COD/Lb. MLVSS/day	1.25	1.09	0.88
Lb. BOD_5/1,000 ft^3/day	193	150	185
Lb. COD/1,000 ft^3/day	325	282	375

TABLE 5. BISSELL POINT UNOX PILOT PLANT
SOLIDS PHASE CHARACTERIZATION

PHASE II

Study	1			2			3		
Cell Residence Time - Days	3.0			6.0 (3.8)			8.8		
MASS BALANCES - % Accounted for									
Oxygen - COD	117			117			108		
Phosphorus	100			105			99		
SOLIDS CHARACTERIZATION	ML	WAS	FE	ML	WAS	FE	ML	WAS	FE
VS/SS	0.70	0.72	0.76	0.72	0.72	0.72	0.81	0.81	0.76
BOD_5/VSS	-	-	0.41	-	-	0.61	-	-	0.33
COD/VSS	-	1.4	1.1	-	1.5	1.9	-	1.4	1.4
N/VSS	0.12	0.11	0.16	0.23	0.12	0.19	0.14	0.09	0.19
P/VSS	0.03	0.03	0.03	0.06	0.02	0.04	0.02	0.02	0.05
BOD_5/COD	-	-	0.37	-	-	0.32	-	-	0.24

Note: ML = Mixed Liquor SS
WAS = Waste Activated Sludge
FE = Final Effluent SS

RETURN SLUDGE			
Total solids - mg/l	38,100	36,100	33,700
Volatile - %	72	72	80
10^6/SVI - mg/l	32,300	22,200	23,800
10^6/SVI (stirred) - mg/l	40,000	28,500	33,300
$\frac{TS}{10^6/SVI}$	1.2	1.6	1.4
SOLIDS PRODUCTION			
VSS/MLVSS/day	0.47	0.38	0.20
VSS/BOD_5 rem	0.66	0.69	0.54
VSS/COD rem	0.44	0.42	0.28
SS/BOD_5 rem	0.90	0.95	0.68
SS/COD rem	0.60	0.58	0.36

Note: Removals are based on total in minus soluble out

and total sample analyses with the difference between the two said to be in the suspended or particulate phase.

Mixed liquor solids settling characteristics were determined in one liter graduates for the conditions established in each study period. No obvious influence of CRT could be found and after a stable soluble COD concentration was achieved, the dominant variable appeared to be the initial solids concentration. These results are reported in Figure 10. The sludge settling rate is given in terms of gpd/sf which is equivalent to 179 times the measured settling rate in ft./hr. These data show close agreement with the results derived from the jointly conducted U.S. EPA - Union Carbide stirred, six foot column studies conducted at Bissell Point.

Figure 11 shows a slight variation of the sludge volume index with mixed liquor suspended solids. The consistently low SVI measurements found in Study 1 may be partially attributable to the high inert suspended solids concentration encountered in the primary effluent preceding and during this investigative period. A dense, excellent settling activated sludge was produced throughout the investigative program.

Several time-dependent profiles were run during each study period to define the minimum solids contacting Time (T_c) to produce a stable soluble COD residual. As shown on Figure 12A, after a solids contacting time of 2 to 3 gm/l per hour very little change in the soluble COD is achieved. Since the pilot plant was operated over a T_c range of 4 to 8, the soluble effluent COD was largely independent of the operating CRT. Figure 12B verifies this observation although there is some indication that performance variability is reduced with older CRT's. However, as reported in Table 3, soluble effluent BOD_5 values do decrease with older CRT systems. Table 6 summarizes the substrate and nutrient removal rates measured during each investigative period. Substrate (BOD_5 or COD) removal rates largely reflect the change in mixed liquor suspended solids mass since similar removal efficiencies are achieved at all investigative CRT's. Nitrogen and phosphorous removal rates on a COD basis at CRT's of 3 and (3.8) days are essentially equivalent but show an approximate 20 percent decline at the oldest CRT investigated, 8.8 days.

Mean secondary pollutant removal efficiencies as a function of the cell residence time were then calculated for the median concentration of primary effluent pollutants (Table 2) using the effluent suspended solids characterization (Table 5) and the measured pollutant removal rates (Table 6). The results are shown in Figure 13. This figure indicates that effluent suspended solids are a problem at younger CRT's due to a lack of bioflocculation, and that the preferred design should encompass a CRT range of about 4 to 7 days.

The measured solids production and substrate removal rates reported in Tables 5 and 6 were utilized to determine the biological coefficients reported in Figure 14. An excellent data fit was found as would be expected from the high accountability of the phosphorus mass balance.

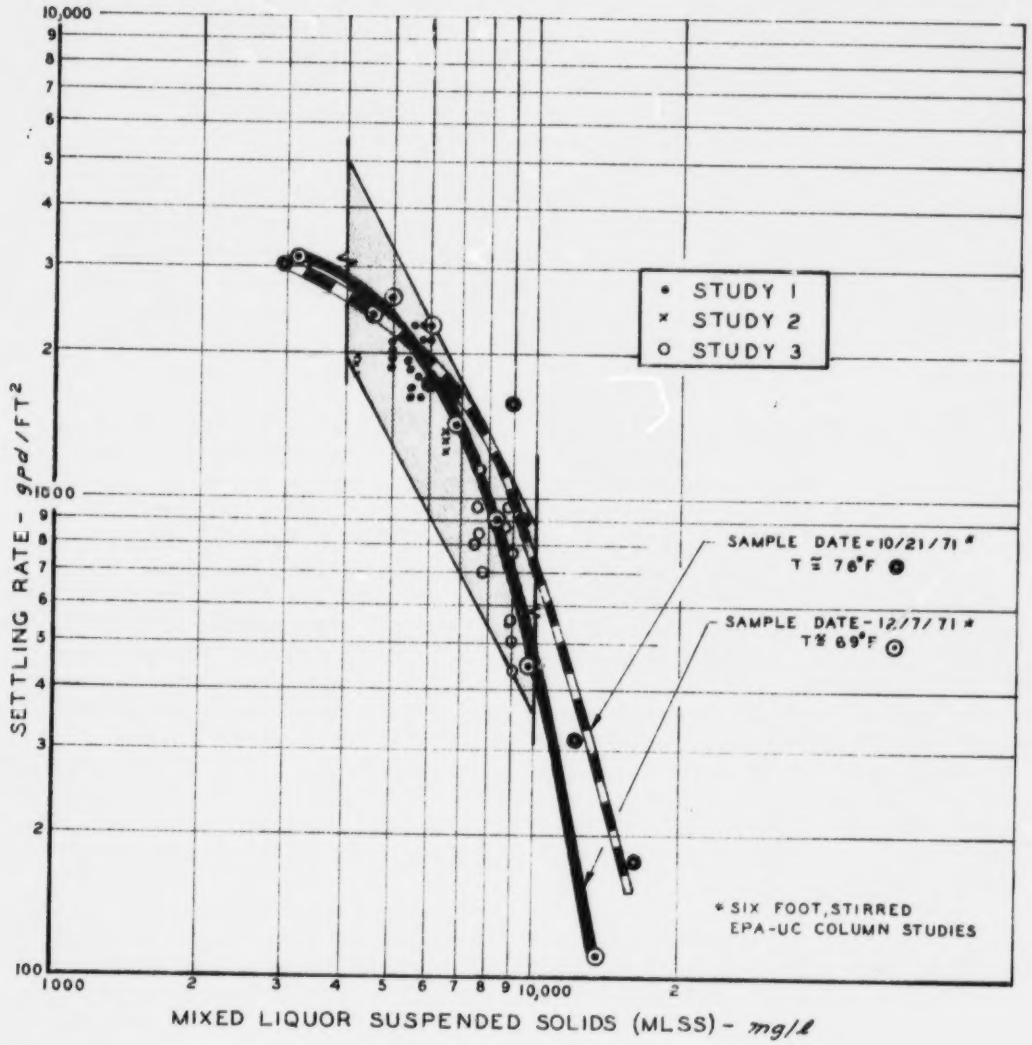


FIGURE 10. MIXED LIQUOR SOLIDS
SETTLING CHARACTERISTICS

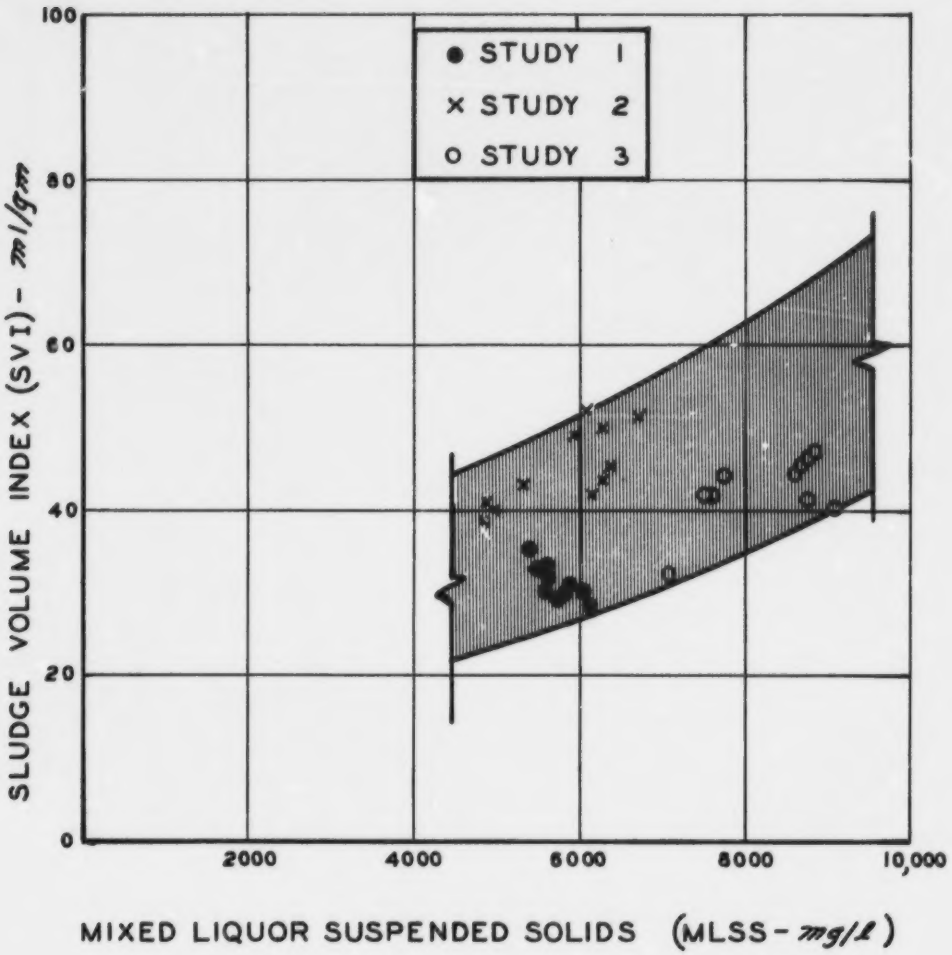


FIGURE 11. SLUDGE VOLUME INDEX VS. MIXED LIQUOR SUSPENDED SOLIDS

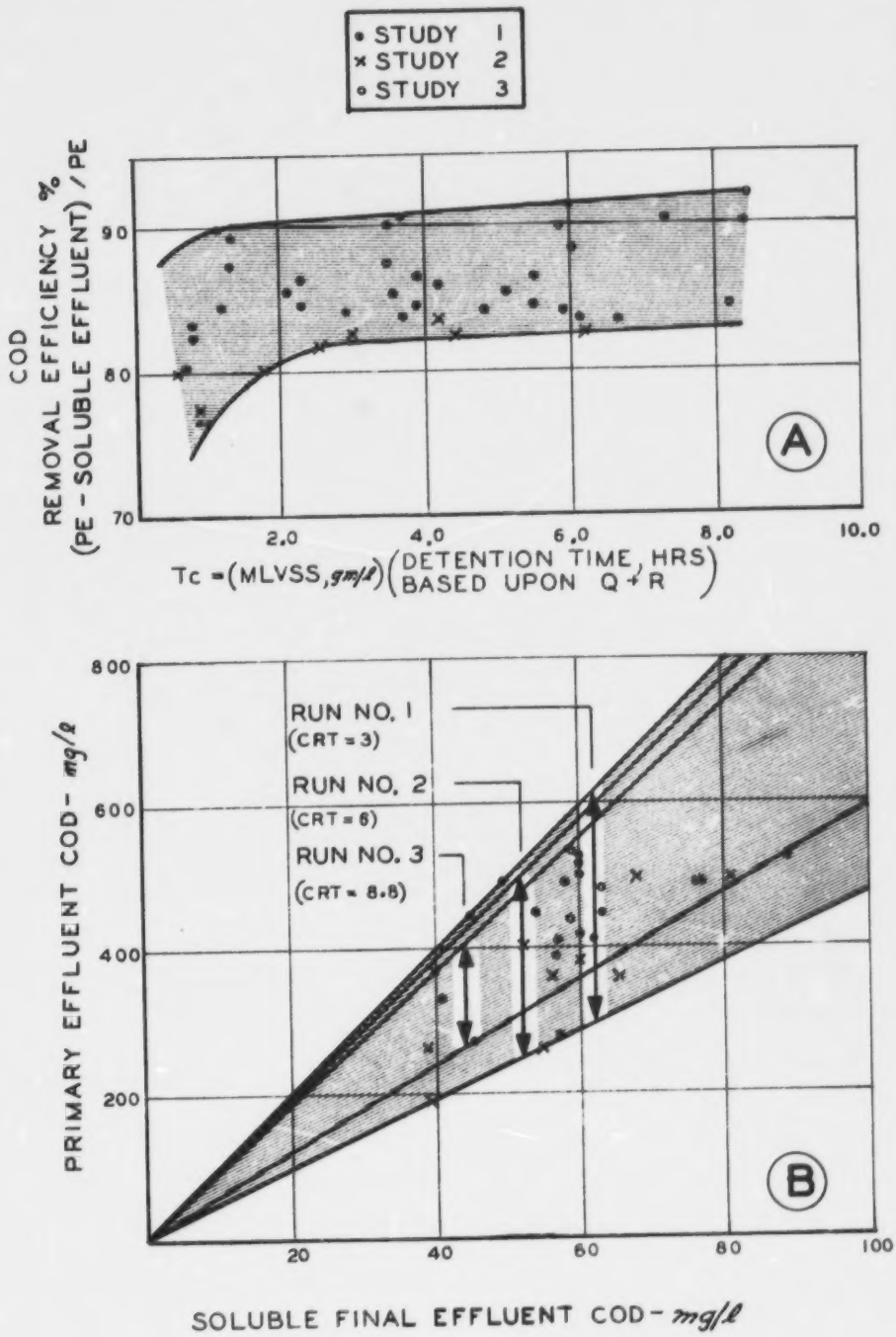


FIGURE 12. COD REMOVALS

TABLE 6. BISSELL POINT UNOX PILOT PLANT
SUBSTRATE AND NUTRIENT REMOVAL RATES

PHASE II

Study	1	2	3
Cell Residence Time - Days	3.0	6.0 (3.8)	8.8
REMOVAL RATES*			
Lb. BOD_5 rem/Lb. MLVSS/day	0.72	0.56	0.38
Lb. COD rem/Lb./MLVSS/day	1.08	0.92	0.73
Lb. P rem/Lb. BOD_5 rem	0.016	0.016	0.014
Lb. N rem/Lb. BOD_5 rem	0.076	0.085	0.077
Lb. P rem/Lb. COD rem	0.011	0.010	0.008
Lb. N rem/Lb. COD rem	0.050	0.051	0.040
TREATMENT CAPABILITY			
Soluble effl. COD = X (PE_{COD}), X =	0.15 ± 0.05	0.16 ± 0.05	0.14 ± 0.03
Secondary Removal Eff. (COD)	85 ± 5	84 ± 5	86 ± 3

*Note: Removals are based on total in minus soluble out

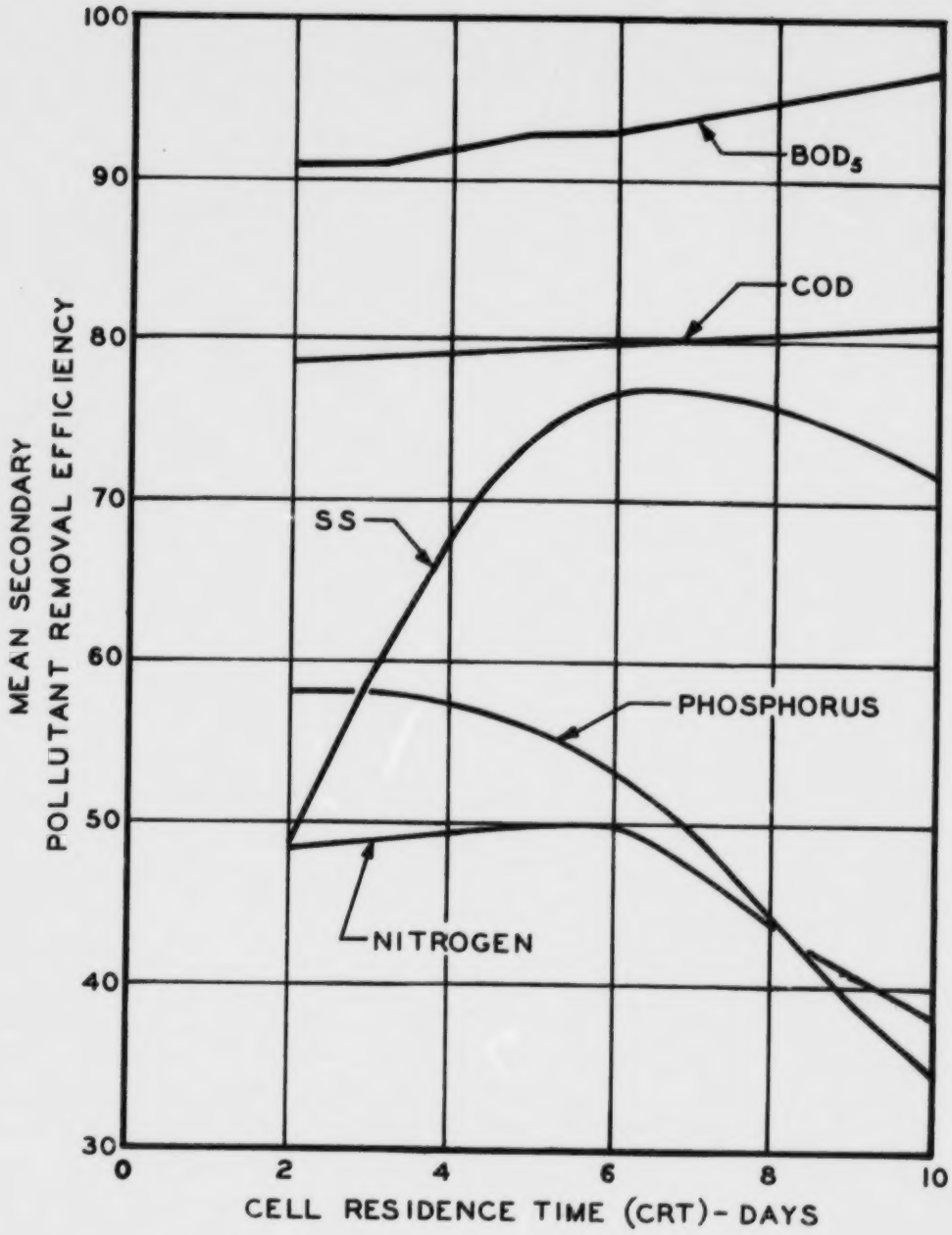
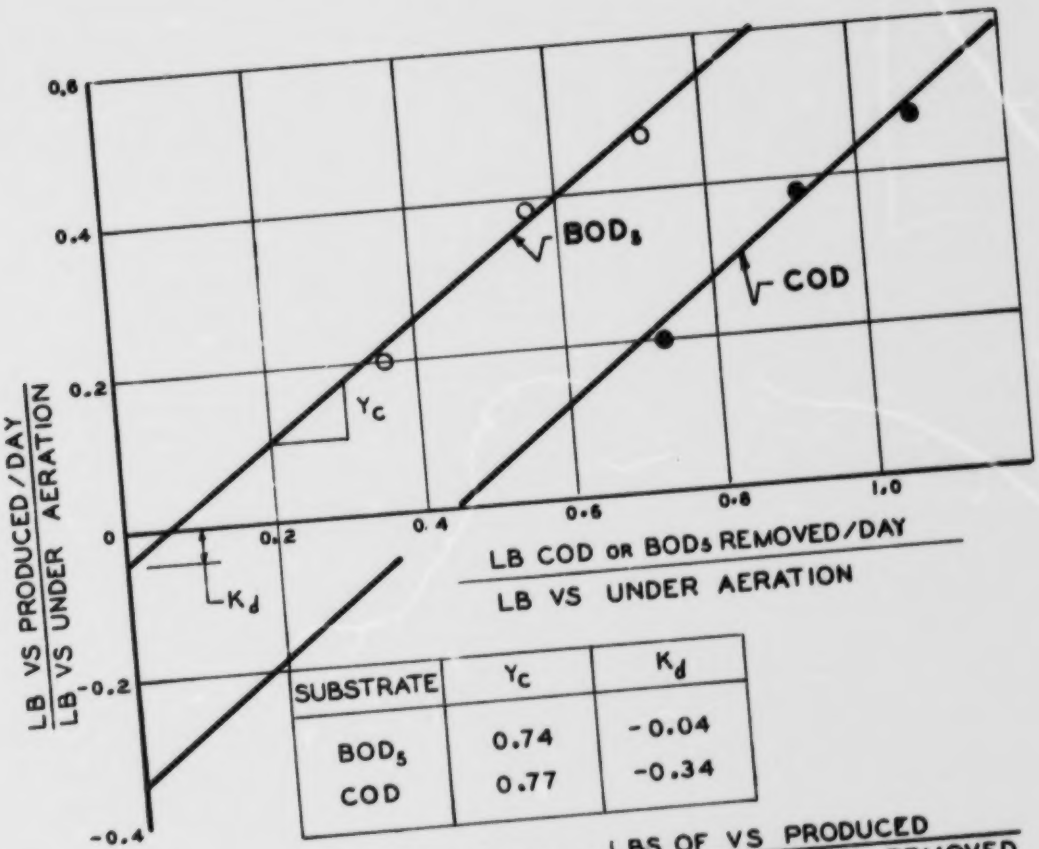


FIGURE 13. MEAN SECONDARY POLLUTANT REMOVAL EFFICIENCY

(PRIMARY EFFLUENT–FINAL EFFLUENT BASIS)



SUBSTRATE	Y_c	K_d
BOD_5	0.74	-0.04
COD	0.77	-0.34

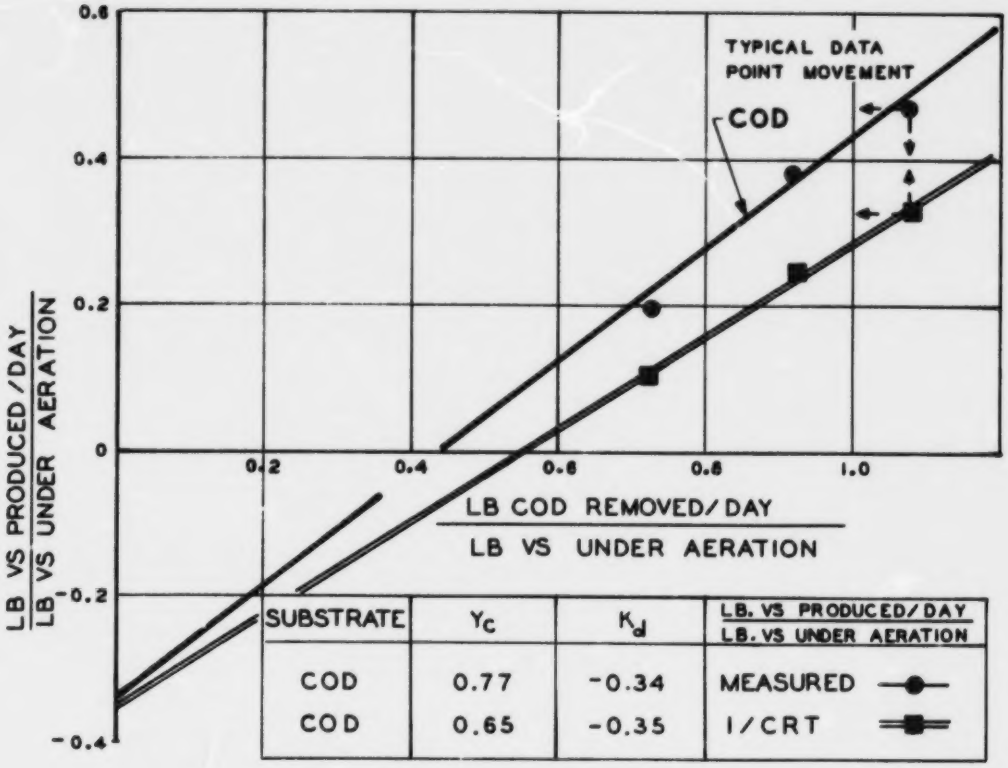
WHERE Y_c = YIELD COEFFICIENT - $\frac{\text{LBS OF VS PRODUCED}}{\text{LB OF SUBSTRATE REMOVED}}$

K_d = DECAY COEFFICIENT - $\frac{\text{LBS OF VS DESTROYED / DAY}}{\text{LB OF MLVSS UNDER AERATION}}$

FIGURE 14. DETERMINATION OF BIOLOGICAL COEFFICIENTS

The solids yield (Y_c) and endogenous decay (K_d) coefficients are determined from this figure; unfortunately, these values are not strictly correct due to solids accumulations in the final clarifier. Although these accumulations were considered in mass balances and solids production values, they could not be introduced back into the pounds of volatile solids under aeration term. If the system were in true equilibrium, it would be expected that the waste solids would be somewhat reduced and the solids under aeration would be increased; thus true data points would be lowered and displaced to the left of the plot. The magnitude of this vector cannot be determined exactly; it is unique to each data point and dependent upon the solids accumulation associated with any given investigative run. The extreme vertical component of this vector can be estimated, however, by plotting measured substrate removal rates against the reciprocal of the measured cell residence time which, at true steady-state conditions, is equivalent to the "pounds of volatile solids produced per day per pound of volatile solids under aeration" term. This assumption ignores the accumulation of solids in the final settler and true data point location can be anticipated to be upward and to the left. Figure 15 shows a plot for each of the techniques of evaluating the data, which shows an indication of data point movement. Generally, prudent design practice would be to select the highest value of waste solids production to assure sufficient solids handling capacity under design conditions and to compensate for lower endogenous destruction rates during colder operating months. Actually, an infinite number of lines can be drawn through any group of data points, each resulting in a different Y_c and K_d. From a design standpoint, as long as the CRT selected for design is within the range investigated, the net value of solids production will be approximately the same, differing only by the tolerance of the plot. Significant error is introduced only upon extrapolation away from the data points to cell residence times significantly lower than the range investigated.

The oxygen utilization values for the investigative program are reported in Table 7. Oxygen requirements as predicted from measured oxygen uptake rates, and COD balances are consistently lower than the oxygen mass as determined from measured gas flow rates and oxygen concentrations as utilized in the reactor. It is felt that the reported oxygen consumption values were somewhat high due to the system leakage, and that the measured MLSS oxygen uptake rates are low due to a lower degree of agitation (less microbial surface exposure) and an inability to fully quantify the high oxygen uptake rates in the first compartment of the reactor. Thus, the oxygen requirements predicted from the COD balance probably provides a more accurate measure of actual system requirements in this pilot plant's test. On this assumption, the system oxygen requirements can be estimated for Bissell Point wastewater from the following relationships:



SUBSTRATE	Y_c	K_d	LB. VS PRODUCED/DAY / LB. VS UNDER AERATION
COD	0.77	-0.34	MEASURED
COD	0.65	-0.35	I/CRT

WHERE Y_c = YIELD COEFFICIENT - $\frac{\text{LBS OF VS PRODUCED}}{\text{LB OF SUBSTRATE REMOVED}}$

K_d = DECAY COEFFICIENT - $\frac{\text{LBS OF VS DESTROYED/DAY}}{\text{LB OF MLVSS UNDER AERATION}}$

FIGURE 15. DETERMINATION OF BIOLOGICAL COEFFICIENTS

TABLE 7. BISSELL POINT UNOX PILOT PLANT
OXYGEN UTILIZATION

PHASE II

Study	1	2	3
Cell Residence Time - Days	3.0	6.0 (3.8)	8.8
OXYGEN UTILIZATION			
Percent of O_2 Supply Utilized	94	87	93
Lb. O_2 utilized/Lb. COD rem	0.60	0.55	0.76
Lb. O_2 predicted from normalized O_2 uptake rates* / Lb. O_2 utilized	0.68	0.50	0.54
Lb. O_2 predicted from COD balance / Lb. O_2 utilized	0.85	0.85	0.92

*Measured by observing dissolved oxygen decline in gently stirred mixed liquor samples collect from each reactor compartment.

$$O_2 \text{ required, mg/l equivalent (to satisfy carbonaceous demand)} = X\left[1 - \frac{BY_c}{1+CRTK_d}\right] + \text{Effl. DO}$$

where X = Primary Effluent COD minus soluble final effluent COD, mg/l

B = Lb. COD/Lb. VS ratio for waste activated sludge.

The above relationship is true only provided that the COD test completely measures all of the carbonaceous oxygen demand and that the substrate COD is converted to waste solids COD on a strict one to one ratio. In view of this qualification and in recognition of the limitation of the Y_c and K_d determinations, a safety factor of at least 10 percent is recommended for use with the preceding relationship. It should also be noted that this equation does not consider the oxygen requirement for nitrification which was not a treatment requirement at St. Louis nor did any nitrogen oxidation occur during the conduct of the pure oxygen pilot plant program. The oxygen requirement for nitrification can be approximated by substrating the nitrogen removed by synthesis from the applied nitrogen and multiplying the resultant residual by 4.6.

CONCLUSIONS

Bissell Point wastewater was found to be readily biodegradable in a pure oxygen activated sludge system. An activated sludge exhibiting excellent densification and settling characteristics was found with the pure oxygen system.

SECTION VI

DESIGN RELIABILITY/COST INVESTIGATIONS

OBJECTIVES

Previous sections of this report have described and summarized the results of the plant and pilot plant investigations at two primary treatment plants. These plants have widely different influent wastewater quality. The intent of this section is to define and enumerate the relative cost magnitude for secondary treatment at these two facilities as they are designed for different degrees of reliability. Specifically, the objectives of this section are to:

1. Develop cost-effective mathematical models to describe the optimum design conditions (and costs) for secondary treatment and waste solids handling as a function of the required design reliability.

2. Establish the optimum point of design reliability as a function of facility expenditure for each plant to illustrate the influence of wastewater quality upon design reliability.

3. Compare the cost differential between the two different plants, as a function of design reliability, to illustrate the influence of wastewater quality upon facility costs and optimum design configuration.

OVERALL ASSUMPTIONS

Both the Bissell Point and Lemay Wastewater Treatment Plants are currently undergoing expansion for secondary treatment for future wastewater conditions. Selection and use of any unit process in the following sections of this report should not be inferred as a specific recommendation for either plant, but only to illustrate the ideas of integrated system performance from a cost-effective standpoint in terms of design reliability.

The following overall assumptions were made for this study:

1. Both plants receive an average daily flow of 100 mgd.

2. The average primary effluent quality for each plant is that enumerated during the eight month plant investigations (Table 1 and Figures 5, 6 and 9).

3. Data and results collected from the pure oxygen pilot plant applies to both Bissell Point and Lemay. This data is used for <u>illustrative purposes only</u>.

COST-EFFECTIVE MODELS

A variety of modeling techniques are available to describe the activated sludge system and other wastewater treatment processes. Other than gaining a fundamental understanding, oftentimes the complexity of these models is not justified in view of the analytical tolerance of the input measurements and variability of wastewater quantity and quality. Examples and discussions of representative work can be found elsewhere[5][6][7][8].

A variety of parameters have been used to characterize the activated sludge process. The mean cell residence time (CRT), as proposed by Pearson[9] and described by Jenkins and Garrison[10], has found popular acceptance in recent years and is utilized in this report. The reader is referred to the previously cited basic references for detailed development of the rationale of cell residence time concepts.

Secondary treatment with the activated sludge system contains four cost sensitive elements. These are the aeration tanks, the oxygen or air supply complex, the final sedimentation unit, and the return and waste activated sludge system. All of these elements are obviously sensitive to the selection of the design CRT and, in turn, the aerator volume. Generally speaking, at a constant CRT which fixes the mass of solids under aeration, shorter aeration detention times will dictate more settling capacity and greater return sludge capability. At some identifiable aeration detention time, therefore, there is a singular cost-effective design.

A cost-effective waste solids handling system strikes an economic balance between solids handling capacities and solids storage capabilities. As applied to waste activated sludge, it is designed at some main stream CRT less than utilized for main stream unit sizing. This is to allow a further mainstream operating flexibility and to assure that sufficient waste solids handling capacities exist should the operator decide to operate the facility at some CRT below the maximum main stream design condition. For the purposes of this report, the waste solids handling sequence has been assumed to incorporate the following sequence of unit processes: gravity thickening, aerobic digestion, storage, vacuum filtration dewatering, and incineration. The capacity of the dewatering and incineration installation is contingent upon the volume provided in the aerobic digester or storage tank. In subsequent paragraphs, cost-effective mathematical models are developed to describe the performance of an activated sludge system and disposal of the waste activated sludge. The models are then expanded for a variety of peaking factors which must be incorporated for different degrees of design reliability. Plant and pilot plant data have been incorporated in every possible instance for illustrative purposes.

ACTIVATED SLUDGE MODEL

In the region of substrate concentrations encountered in municipal wastewater treatment, the specific growth rate of the activated sludge system is proportional to the substrate concentrations. This has led to the following expression for steady-state conditions.

$$\frac{1}{CRT} = \frac{X}{MLVSS} Y_c - K_d \quad \text{---------- (1)}$$

where $\frac{1}{CRT}$ = net growth rate ($days^{-1}$)

$\frac{X}{MLVSS}$ = substrate removal rate,

$$\left[\frac{\text{lbs. substrate removal per day}}{\text{lb. mixed liquor volatile suspended solids}}\right]$$

Y_c = yield coefficient,

$$\left[\frac{\text{lbs. volatile solids produced}}{\text{lb. substrate removed}}\right]$$

K_d = endogenous respiration coefficient,

$$\left[\frac{\text{lb. volatile solids destroyed per day}}{\text{lb. volatile solids under aeration}}\right]$$

This equation may be rewritten to solve for the MLVSS at any CRT:

$$\text{MLVSS, mg/l equivalent} = \frac{CRT\ XY_c}{1+CRTK_d} \quad \text{---------- (2)}$$

where CRT = cell residence time (days)

X = substrate removal (mg/l)

The "mg/l equivalent" term is introduced for mathematical simplicity; multiplication of this term by the average design flow and 8.34 will yield the correct mass value.

Assuming no creation nor removal of influent inert suspended solids (S_1) in the activated sludge system, the total mixed liquor suspended solids are:

$$\text{MLSS, mg/l equivalent} = CRT\left[S_1 + \frac{XY_c}{1 + CRTK_d}\right] \quad \text{---------- (3)}$$

And the actual MLSS at any aerator detention time is:

$$\text{MLSS, mg/l} = \frac{24}{D_t} \left[\text{CRT} \left(S_1 + \frac{XY_c}{1 + \text{CRT}K_d}\right)\right] \text{ ---------- (4)}$$

where D_t = Aerator detention time based on Q (hours)

This equation establishes the design variable D_t. The cost of achieving different MLSS concentrations at a given CRT can be established with an aerator unit cost (dollars per unit volume).

If it is assumed that the substrate COD removal is fully quantified and that the fraction that is not oxidized is converted to new cellular COD on a 1:1 basis, a COD balance can be written around the biological system which describes the system's oxygen requirement. In this equation:

$$\text{Oxygen Requirement} = X - \text{COD}_{\text{cells}} + \text{effluent DO} \text{ ---------- (5)}$$

the COD of the cells is equivalent to the COD of the waste activated volatile solids. The waste activated volatile solids are equal to equation (2) divided by the CRT. Thus, the system's oxygen requirement is:

$$O_2 \text{ requirement, mg/l equivalent} = X\left[1 - \frac{BY_c}{1 + \text{CRT}K_d}\right] + E \text{ ---- (6)}$$

Where B = waste activated sludge COD/VSS ratio (lb./lb.)

E = effluent DO (mg/l)

To convert this equation from a theoretical condition to an applied peak requirement, equation 6 must be adjusted as follows:

$$O_2 \text{ supply, tons/day} = \frac{8.34Q}{2000} \left[X \left(\frac{1-BY_c}{1+\text{CRT}K_d}\right) + E\right] \frac{(K_1)(K_2)(P_1)}{G} \text{ -- (7)}$$

where Q = average daily flow (mgd)

K_1 = COD mass balance adjustment factor (unitless)

K_2 = Aeration detention time adjustment relationship (unitless)

P_1 = Oxygen supply peaking factor (unitless) for the defined degree of reliability.

G = Oxygen transfer efficiency (unity scale)

The parameter K_2 is provided to reflect the exaggeration or dampening of oxygen requirements as influenced by the aerator detention time. Long detention time units, for example, buffer out diurnal swings of applied substrate and the corresponding oxygen supply requirements. Since all diurnal plant data was

collected at four hour intervals, some factor had to be introduced to relate the oxygen requirements to detention times other than four hours. This was done by using the average data contained in Figure 6, and assuming that the variation indicated was valid for any given day. Assigning a unity value to the four-hour observance (83.3 percent less than) and weighting all other observations appropriately, the variation from one hour per day (95.8 percent less than) to 12 hours per day (50 percent less than) could be established in comparison to the standard four hours per day interval. This was done for both plants using a package computer program* and the resultant polynominal expressions were found essentially equivalent, given an average definition of K_2 as follows:

$$K_2 = 1.28 - 0.078D_t + 0.003\ D_t2 \quad \text{---------- (8)}$$

where D_t = aeration detention in hours based upon Q

Settling velocities of activated sludge floc are dominated by the applied concentrations of the sludge. These settling velocities define the surface overflow rate (SOR) that cannot be exceeded, which in turn, established the required surface area for solids-liquid separation. Thus, the required surface area for sedimentation is:

$$\text{Required surface area, SF} = \frac{Q(10^6)P_2}{(K_3)(K_4)} \quad \text{---------- (9)}$$

where K_3 = relationship describing variance of activated sludge settling rate, gpd/SF, with activated sludge concentration

K_4 = adjustment factor to relate measurement inadequacies to applied conditions, i.e., temperature, physical geometry of test cylinder, etc.

P_2 = hydraulic peaking factor (unitless)

The parameter K_3 is developed from pilot plant data such as contained in Figure 10. This data, using the bottom of performance envelope, results in the following expression for K_3:

$$K_3, \frac{gpd}{SF} = \frac{F_1\ 10^6}{MLSS^{F_2}} = \frac{3400\ (10^6)}{MLSS^2} \quad \text{---------- (10)}$$

*(**polfit of SBC Call/370)

The return sludge requirement (R) is found with a solids balance around the final sedimentation system, where:

(MLSS, mg/l) (Q + R) = R (return sludge, mg/l)

or

$$R = QP_2 \left[\frac{\text{MLSS}}{\text{return sludge - MLSS}} \right] \text{concentration} \quad \text{---------- (11)}$$

The MLSS concentration is found from Equation 4 and the return sludge concentrations can be represented by:

$$\text{Return sludge, mg/l} = \frac{F(10^6)}{SVI} \quad \text{---------- (12)}$$

where F = adjustment factor for actual return sludge concentration in comparison to that predicted after 30 minutes settling (unitless)

SVI = sludge volume index (ml of settled sludge at 30 minutes per gram of MLSS)

The SVI term can be assumed constant or developed in terms of the MLSS, assuming the latter and utilizing the information contained in Figure 11, the upper edge of the performance envelope is described by the following relationship:

$$SVI = H_1 e^{H_2 MLSS} = 28e^{0.0001\ (MLSS)} \quad \text{---------- (13)}$$

WASTE ACTIVATED SLUDGE MODEL

The steady-state waste activated sludge quantity is derived by dividing Equation (3) by the CRT and subtracting the effluent suspended solids. The resultant expression, adjusted for maximum day conditions, is given below:

$$\text{Waste Activated Sludge, mg/l equivalent, WAS} = \left[S_1 + \frac{XY_c}{1+CRTK_d} - S_2 \right] P_3 \quad \text{- (14)}$$

where S_2 = effluent suspended solids (mg/l)

P_3 = maximum day solids production factor (unitless)

Its volatile and inert fractions are as follows:

Waste Activated Volatile Solids, mg/l equivalent = WAVS

$$= \left[\frac{XY_c}{1 + CRTK_d}\right] \left[1 - \frac{S_2}{S_1 + \frac{XY_c}{1+CRTK_d}}\right] P_3 \quad \text{---------- (15)}$$

Waste Activated Inert Solids, mg/l equivalent = WAIS

= WAS - WAVS = equation 14 - equation 15

$$= \left[(S_1 + \frac{XY_c}{1+CRTK_d} - S_2) - (\frac{XY_c}{1+CRTK_d}) \left(1 - \frac{S_2}{S_1+\frac{XY_c}{1+CRTK_d}}\right)\right] (P_3) \text{ -- (16)}$$

The first unit process in the handling sequence is a gravity thickener. This unit process was selected because of the superior densification characteristics exhibited by the pure oxygen sludges. Appropriate sizing of the unit is given by the following relationship:

$$\text{Required Area, SF} = \frac{[8.34][Q][WAS]}{T_1} \quad \text{---------- (17)}$$

where WAS = equation 14

T_1 = solids loading rate, pounds of dry solids/SF.day

The hydraulic flow of the thickened waste activated sludge is found with the following equation:

$$\text{Thickened sludge flow: mgd} = \frac{[Q][WAS]}{C_1} \quad \text{---------- (18)}$$

where WAS = equation 14

C_1 = thickened solids concentration (mg/l)

The aerobic digestion/storage system is incorporated to maintain the waste solids in an aerobic state to assure no deterioration of solids dewaterability. It also serves the dual purposes of further volatile solids reduction and dampening of the solids load upon the subsequent unit processes. There is one definable volume for this system which provides a cost-effective balance between the aerobic digester sizing and the solids handling capacity of the subsequent unit processes. The volatile solids residual following aerobic digestion can be found with the following relationship:

$$WAVS_R = \frac{WAVS}{P_3} \left[\frac{\frac{XY_c}{1 + CRT_o K_d}}{\frac{XY_c}{1 + CRTK_d}} \right] (K_5)(P_4)$$

$$= \left[1 - \frac{S2}{S_1 + \frac{XY_c}{1 + CRTK_d}}\right] \left[\frac{XY_c}{1 + CRT_o K_d}\right] (K_5)\, P_4 \text{ ------- (19)}$$

where CRT_o = overall system CRT (days)

P_4 = relationship describing consecutive day generation of waste solids (unitless)

K_5 = adjustment factor for accumulation of nonbiodegradable volatile solids (unitless)

P_4 is developed from the data contained in Figure 9 using the average results. Maximum results are not used because of the storage capacity in the aerator when operated at a CRT less than the maximum main stream design condition. The relationships derived for each plant are of the following form:

Bissell Point:

$$P_4 = M_1 (CRT_o - CRT)^{M_2} = 1.59 (\Delta CRT)^{-0.17} \text{ ---------- (20)}$$

Lemay:

$$P_4 = 1.39 (\Delta CRT)^{-0.10} \text{ ---------- (21)}$$

The optimum overall cell residence time, CRT_o, dictates the required aerobic digester volume according to the following:

$$\text{Volume, CF} = \frac{10^6}{7.48} \text{ [thickened sludge flow] } [CRT_o - CRT] \frac{P_4}{P_3} \text{ --- (22)}$$

where thickened sludge flow = equation 18

with a required oxygen supply equal to:

$$O_2 \text{ supply, tons/day} = \frac{(8.34)\ QB}{2000} [WAVS - WAVS_r] \frac{K_1}{G} \text{ ------ (23)}$$

where WAVS = Equation 15

$WAVS_r$ = Equation 19

In recognition of the interrelationship between applied suspended solids and filter yield rates (Lbs./SF.Hr). The filter yield rate (Lb./SF.Hr) is assumed as equal to the solids concentration of the applied solids on a percent basis (unity scale). The applied solids concentration to the vacuum filter dewatering system is equal to:

concentration of aerobically digested solids, % =

$$C_2 = \frac{C_1}{10^4} \left[\frac{WAVS_r + WAIS\left(\frac{P_4}{P_3}\right)}{WAS}\right] \text{ ---------- (24)}$$

where $WAVS_r$ = Equation 19

WAIS = Equation 16

WAS = Equation 14

and the required filter area is:

$$\text{Filter area, SF} = \frac{\left(WAVS_r + WAIS\left[\frac{P_4}{P_3}\right]\right) Q\ (8.34)(K_6)}{C_2\ (H_3)} \text{ ---------- (25)}$$

where H_3 = hours of daily operation

K_6 = adjustment for accumulation of precipitated solids due to conditioning chemicals

which reduces to:

$$\text{Filter Area, SF} = \frac{Q\ (8.34)\ (K_6)\ (WAS)\ (10^4)}{C_1\ H_3} \text{ ---------- (26)}$$

where WAS = Equation 14

Equation 24 shows that the assumption that the filter yield rate is equivalent to the applied solids concentration results in a case where the loss of solids concentration due to aerobic digestion results in an equivalent loss of filter yield rate. Thus, the advantages of volatile solids destruction during aerobic digestion are only demonstrated in conditioning chemical requirements and an absence of septicity.

Multiple hearth incinerator loadings can be expressed in terms of pounds of wet solids per square foot per hour. Therefore, the required incinerator sizing is:

$$\text{Incinerator area, SF} = \frac{(WAVS_T + WAIS\ [\frac{P_4}{P_3}])\ Q(8.34)\ K_6}{C_3 H_3 I_1} \quad \text{----- (27)}$$

where $WAVS_T$ = Equation 19

$WAIS$ = Equation 16

C_3 = concentration of solids in dewatered cake (decimal percentage)

I_1 = incinerator loading rate $(\frac{\text{lbs. W.S.}}{\text{SF.Day}})$

DESIGN RELIABILITY/COST INVESTIGATIONS

Computer programs (basic language using the SBC Call/370 system) were developed to solve for the optimum aeration detention time (based on Q) for the secondary activated sludge system (AS - Appendix B) and for the optimum aerobic digester (storage) volume for the waste activated sludge system (WAS - Appendix C) using the previously developed relationships, input parameters established during the plant and pilot plant investigations, design assumptions, and unit costs.

Tables 8 and 9 summarize the parameters for the activated sludge and waste activated sludge programs. All input parameters for the activated sludge program are assumed to be the same except those which define the character of the wastewater (X and S_1) and its variability from average day conditions (P_1 and P_2). The design CRT for the activated sludge system was selected at 7 days based upon the data contained in Figure 13. This cell residence time is slightly greater than point of maximum effluent clarity (lowest effluent suspended solids). From an operational standpoint, the activated sludge system will provide successful operation up to this CRT. The cell residence time used to define the quantity of waste activated sludge must be less than this CRT. This is to assure an operational flexibility in both the main stream and solids handling system. Figure 13 indicates that adequate effluent clarification can still be achieved at a CRT of 4 days; this establishes the CRT for the waste activated sludge system. All input parameters for the waste activated sludge program are the same except those which define the character of the wastewater (X and S_1) and the variability of waste solids generation (P_3 and P_4).

At this point, it is considered worthwhile to discuss the impact of the Y_c and K_d coefficients used in this report. The reader will note that the oxygen required per pound of COD removed can be superficially quantified as:

$$1 - \frac{1.4\ Y_c}{1 + CRTK_d}$$

TABLE 8. PARAMETERS FOR ACTIVATED SLUDGE PROGRAM

No.	Parameter	Units	Term	Source	Value: Bissell Point	Value: Lemay
1.	Cell Residence Time	days	CRT	Figure 13	7	7
2.	Substrate Removed, COD	mg/l	X	Figure 12 Table 1	395	150
3.	Cell Yield Coeff.	lb/lb	Y_c	Figure 14	0.77	0.77
4.	Endogenous Decay Coeff.	$\frac{lb/day}{lb}$	K_d	Figure 14	0.34	0.34
5.	Influent Inert SS	mg/l	S_1	Table 1	35	27
6.	Average Daily Flow	mgd	Q	Assume	100	100
7.	Waste Activated Sludge COD/VS Ratio	lb/lb	B	Table 5	1.4	1.4
8.	Effluent DO	mg/l	E	Assume	4	4
9.	Efficiency of oxygen transfer	unity scale	G	Assume	0.90	0.90
10.	COD Mass Balance Adjustment Factor	----	K_1	Assume	1.10	1.10
11.	Aeration Detention Time Adjustment Factor	----	K_2	Text Figure 6	$1.28-0.07D_t+0.003D_t^2$	
	(where D_t = aeration detention time, hours = program variable)					
12.	Oxygen Peaking Factor	----	P_1	Figure 6	See Table 11	
13.	MLSS Settling Velocity	$\frac{gpd}{SF}$	K_3	Figure 10	$\frac{F_1(10^6)}{MLSS^{F_2}}$	
	(where $F_1 = 34000$, $F_2 = 2$)					
14.	Temperature/Physical Adjustment Factor	----	K_4	Assume	0.90	0.90
15.	Hydraulic Peaking Factor	----	P_2	Figure 5	See Table 11	
16.	Sludge Volume Index	ml/g	SVI	Figure 11	$H_1e^{H_2(MLSS)}$	
	(where $H_1 = 28$, $H_2 = 0.0001$)					
17.	Settled Sludge Concentration Factor	----	F	Table 5	1.4	1.4

TABLE 9. PARAMETERS FOR WASTE ACTIVATED SLUDGE PROGRAM

No.	Parameter	Units	Term	Source	Value	
					Bissell Point	Lemay
1.	Cell Residence Time	days	CRT	Figure 13	varies	varies
2.	Effluent SS	mg/l	S_2	Assume	25	25
3.	Average Maximum Day Solids Generation Factor	-	P_3	Figure 9	1.56	1.39
4.	Gravity Thickener Loading Rate	$\frac{lb}{SF.day}$	T_1	Assume	25	25
5.	Thickened Solids Concentration	mg/l	C_1	Assume	50,000	50,000
6.	Accumulation Factor for Nonbiodegradable Volatile Solids	- [Where CRT_o = overall cell residence time (days) - program variable]	K_5	Assume	At CRT_o 0-10 10-15 15-20 20-25 25-30	K_5 1.00 1.05 1.10 1.15 1.20
7.	Relationship Describing Consecutive Day Generation of Waste Solids	-	P_4	Figure 9 where M_1 M_2	$M_1 (CRT_o - CRT)^{M_2}$ 1.59 -0.17	 1.39 -0.10
8.	Adjustment for Accumulation of Precipitated Solids due to conditioning chemicals	-	K_6	Assume	1.05	1.05
9.	Hours of Daily operation	Hrs.	H_3	Assume	24	24
10.	Concentration of cake solids	decimal fraction	C_3	Assume	0.15	0.15
11.	Incinerator Loading Rate	$\frac{lb.\ W.S.}{SF.day}$	I_1	Assume	10	10

12. Parameters X, Y_c, K_d, S_1, Q, K_1, B, and G defined in Table 10.

At a CRT of 0, a negative value of 0.08 is predicted with a Y_c of 0.77. If one applies a more conventionally reported Y_c value of 0.35, a value of 0.51 pounds of oxygen per pound of COD removed is predicted. As pointed out in the previous chapter, potential errors are encountered as one extrapolates the Y_c and K_d coefficients outside of the CRT range investigated. Practically, the designer is only concerned with the net result of these two coefficients. As shown below, the difference in net result of the coefficients used in this report and those conventionally reported is relatively insignificant.

	$\frac{\text{lbs. } O_2 \text{ required}}{\text{lb. COD removed}}$	
CRT (days)	$Y_c = 0.77$, $K_d = 0.34$	$Y_c = 0.35$, $K_d = 0.05$
4	0.54	0.60
5	0.61	0.61
6	0.65	0.62
7	0.68	0.64

Indeed, the values used provide a little extra contingency in solids production at the low CRT and in oxygen supply at the high CRT, a prudent place to be in both instances.

Unit costs for the treatment components contained in the two programs are summarized in Table 10. Annual costs were prepared by amortizing the cost of capital facilities over twenty years at 7 percent interest. These facility costs were developed using manufacturers' price quotations for all major items of equipment (pumps, oxygen production and application equipment, clarification and thickening equipment, vacuum filters, and incinerators) and establishing quantities for all major items of work (excavation, piling, concrete, steel, major and minor piping, valving, etc.) These prices reflect the actual unit costs developed for an examination of pure oxygen secondary treatment alternate at Bissell Point and similar large-scale design reports prepared in the Spring of 1973 with due regard to the relative local costs of construction. They include all auxiliary expenditures (conduits, service tunnels, control centers, buildings, yardwork, instrumentation, plumbing, heating, ventilating, air conditioning, electrical, service water, site preparation, engineering, inspection, legal and administrative costs) and reflect the use of multiple parallel system components. The listed annual costs include the expenditures for chemicals, fuel and water at current prices plus a price of 1.25 cents per Kilowatt-hour of brake horsepower energy at average day requirements. Manpower and land expenditures were excluded. Aeration expenditures reflect the sealed tank construction and the incorporation of mixers and compressors common to pure oxygen activated sludge treatment. Oxygen production equipment utilizes a multiple usage of cryogenic, pressure swing absorption and liquid oxygen storage; this complex was designed to be independent of an outside supply. Sedimentation facilities were circular in orientation, twelve feet deep, and equipped with surface skimming and multiple-point sludge collection. The gravity thickeners were also circular in nature, fifteen feet deep, enclosed, and equipped with

TABLE 10. UNIT COSTS FOR PROGRAM COMPONENTS

Component	Unit	Annual Costs
Aeration Tank	$/1000CF	750
Oxygen Production	$/ton day capacity	1,400
Sedimentation	$/1000SF	5,200
Return Sludge	$/mgd Capacity	2,600
Gravity Thickening	$/SF	7.1
Aerobic Digestion (storage)	$/CF	0.70
Oxygen Supply	$/ton day capacity	2,300
Vacuum Filtration	$/SF	130
Incineration	$/SF	76

ozonation facilities for odor control. The dewatering and incineration complex includes standby units for maximum day processing. The incineration facility is equipped with an afterburner and advanced scrubbing devices for air pollution and plume control.

Table 11 gives the peaking factors for different degrees of design reliability. These factors are established from the plant data contained in Figures 5 and 6 which give the percent less than occurrence of hydraulic flows and primary effluent COD mass. These factors are introduced in the activated sludge computer program to determine the optimum cost-effective aeration detention time as a function of the design reliability.

The results of the design reliability/cost investigations are summarized in Table 12. To find the optimum point of design reliability we have developed a benefit/cost ratio, where the benefit is defined as the annual hours of designed successful operation. This table shows that the optimum cost-effective point for secondary activated sludge treatment at both plants is in the order of 95 to 97.6 percent reliability. A failure interval of four hours per week corresponds to a 97.6 percent reliable design. Increasing this reliability up to 99.91 percent (a failure interval of four hours per six months) results in a surprisingly small deviation from the optimum benefit/cost ratio. Deviations from optimum design conditions are slightly more pronounced at Lemay than at Bissell due to the higher variability of the oxygen supply and hydraulic peaking factors (P_1 and P_2) from average day conditions. In a general sense, it can be anticipated that a design reliability in the order of 97.6 percent is nearly optimum for most wastewater treatment facilities. Oxygen and hydraulic deviations from average conditions substantially greater than utilized in the example can be anticipated to dictate a higher design reliability for optimum cost-effectiveness; conversely, oxygen and hydraulic peaking factors substantially lower than that utilized in the example promote a lower design reliability for optimum cost-effectiveness.

Figures 16 and 17 show the variability of secondary treatment costs as a function of the aeration detention time (based on Q) for the optimum point of design reliability. These figures graphically illustrate the trade-off between secondary activated sludge components. Optimum design conditions at both plants result an aeration expenditure of about sixty percent of the total annual costs. Furthermore, since annual expenditures for oxygen production range from one-half (Bissell Point) to one-third (Lemay) of the sedimentation facilities, it can be inferred that hydraulic peaking factors have the greatest impact upon cost-effective plant design and; if at all possible, efforts should be expanded to dampen their variability. The traditional operating tools, oxygen supply and return sludge capability, are relatively insensitive contributors to total annual costs and over-design of these facilities will have little bearing upon the resultant total facility costs.

TABLE 11. PEAKING FACTORS VERSUS DESIGN RELIABILITY

Design Reliability Up to	Occurrence-Percent less than (Design Reliability)	Bissell Point		Lemay	
		P_1	P_2	P_1	P_2
12 hours/day	50	1.00	1.00	1.00	1.00
4 hours/day	83.3	1.30	1.18	1.40	1.20
	90	1.42	1.24	1.52	1.26
	95	1.58	1.32	1.70	1.35
4 hours/week	97.6	1.72	1.40	1.85	1.44
	98.5	1.85	1.46	2.00	1.52
4 hours/month	99.44	2.02	1.60	2.35	1.70
4 hours/3 months	99.82	2.25	1.72	2.62	1.88
4 hours/6 months	99.91	2.40	1.80	2.80	1.96

P_1 = oxygen supply peaking factor (Figure 6)

P_2 = hydraulic peaking factor (Figure 5)

TABLE 12. DESIGN RELIABILITY VERSUS BENEFIT/COST RATIO

Design Reliability (%)	Benefit Annual Hours of Designed Successful Operation (Hours)	BISSELL POINT Optimum Aerator D_t (Hours)	BISSELL POINT Annual Facility Costs ($1000)	BISSELL POINT Normalized Benefit/Cost Ratio (--)	LEMAY Optimum Aerator D_t (Hours)	LEMAY Annual Facility Costs ($1000)	LEMAY Normalized Benefit/Cost Ratio (--)
50	4380	3.5	2,350	0.60	2.1	1,420	0.60
83.3	7300	3.7	2,530	0.93	2.3	1,530	0.93
90	7884	3.7	2,590	0.98	2.3	1,570	0.97
95	8272	3.8	2,670	0.9995	2.4	1,610	0.997
97.6	8552	3.9	2,760	1.00	2.4	1,660	1.00
98.5	8629	3.9	2,800	0.994	2.5	1,700	0.98
99.44	8712	4.1	2,910	0.97	2.5	1,790	0.94
99.82	8744	4.2	3,010	0.94	2.6	1,860	0.91
99.91	8752	4.2	3,080	0.92	2.6	1,900	0.89

Note: Normalized Benefit Cost Ratio $= \dfrac{\left[\dfrac{\text{Annual Hours of Designed Successful Operation}}{\text{Annual Facility Costs}}\right]_{\text{Reliability}}}{\left[\dfrac{\text{Annual Hours of Designed Successful Operation}}{\text{Annual Facility Costs}}\right]_{\text{Optimum Reliability}}}$

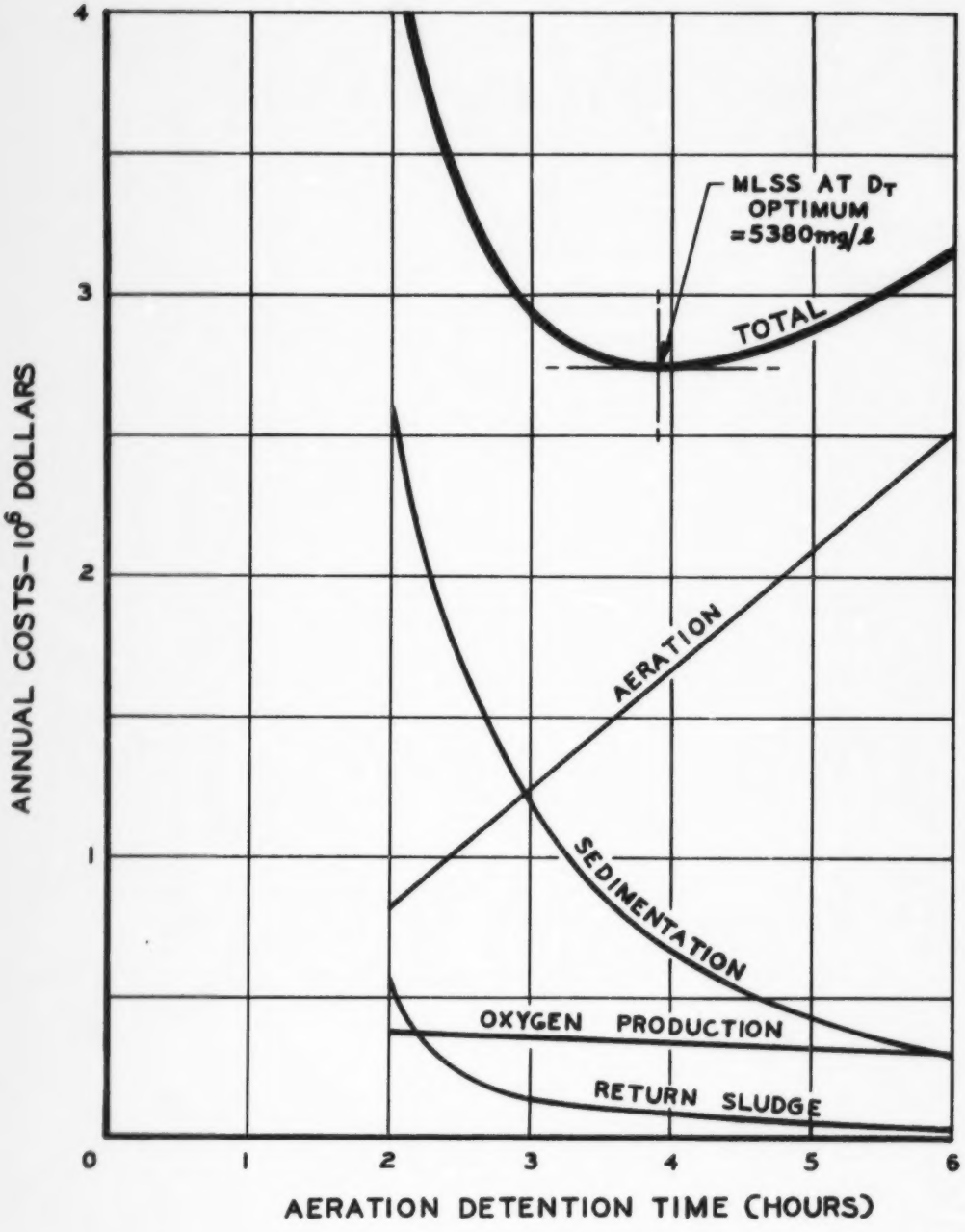


FIGURE 16. BISSELL POINT: SECONDARY TREATMENT COSTS VS. AERATION DETENTION TIME

(DESIGN RELIABILITY - 97.6 %)

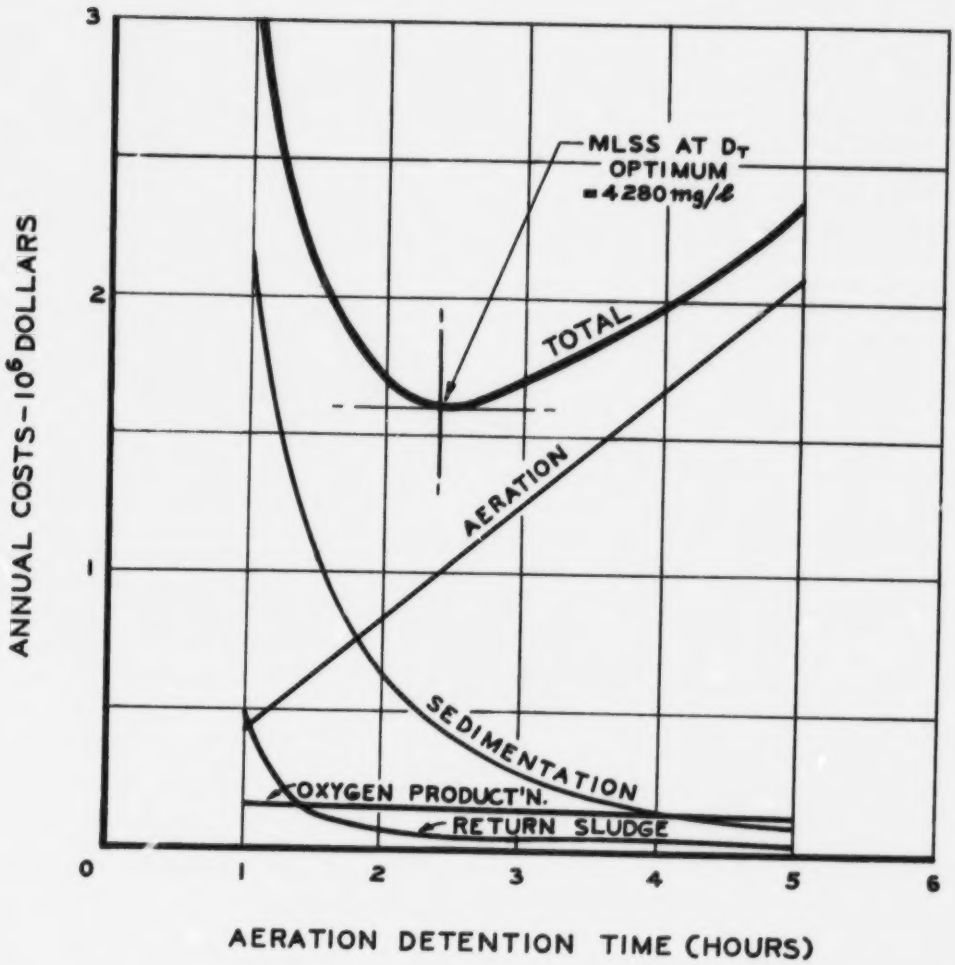


FIGURE 17. LEMAY: SECONDARY TREATMENT COSTS VS. AERATION DETENTION TIME (DESIGN RELIABILITY - 97.6 %)

The influence of wastewater quality upon optimum facility sizing is illustrated in Figures 16 and 17. Total facility costs at Bissell Point, which provides a potential pollutant mass (COD) removal of 2.6 times that of Lemay, are 1.7 times greater than Lemay. This is largely due to Bissell's expanded aerator system which is 1.6 times larger than Lemay's aeration complex. As demonstrated in these figures, Bissell Point's pollutant mass removals justify operation at a 25 percent increase in mixed liquor suspended solids concentrations. Table 13 summarizes the design criteria for the optimum cost-effective conditions described in Figures 16 and 17. This summary shows that optimum aerator design conditions are remarkably close to the old standard BOD_5 loading of 0.35 lbs. of BOD_5 per day per pound of mixed liquor volatile suspended solids for standard rate activated sludge systems. Maximum return sludge rates at both plants are well below the recommended design maximum of 50-75 percent(11)(12) due to the superior densification characteristics exhibited by pure oxygen sludges. Both plants also exhibit an oxygen supply capability of 150 to 200 percent over average day conditions, which is also conventionally recommended(11)(12). However, at Lemay the optimum surface overflow rate for final settling exceeds the conventionally applied 800 to 1000 gpd/sf standard(11)(12). In a general sense, it can be concluded that stronger wastewaters are certainly more cost-effective in terms of dollars expenditure per unit mass of pollutant removed and that stronger wastewaters justify an increase in operating MLSS concentrations with a compensating increase in sedimentation area. It can be also inferred that the pure oxygen activated sludge system operates most effectively at loading criteria similar to those that have been applied successfully with air activated sludge systems. Indiscriminate use of "standard" design overflow rates for final sedimentation and return sludge capabilities can result in system design that can be neither design, performance, nor cost-effective; however, when in doubt it is better to provide too much rather than too little. Providing oxygen supply capability between 150 to 200 percent over average day conditions is cost-effective, and exerts little influence over total facility expenditures.

Figure 18 shows the optimum waste activated sludge handling system costs as a function of the main stream secondary treatment CRT. Waste activated sludge thickening was found to be cost-effective for both plants at all conditions. At Bissell Point aerobic digestion (storage) was found to be not cost-effective at any main stream CRT. However, the annual cost differential between a system containing an aerobic digester (storage) unit with a volume for one additional CRT and one excluding aerobic digestion was found to be only in the order of 5 percent. Aerobic digestion (storage) equivalent to an overall CRT of 4 days was found to be cost-effective (a maximum savings of 5 percent at a secondary treatment CRT of one day) for Lemay. Above a secondary treatment CRT of 4 days, a cost-effective system at Lemay excluded an aerobic digestion storage unit for a savings of two to five percent. All in all, the savings or liability associated with providing an aerobic digestion (storage) volume equivalent to one day of maximum sludge production at any main plant CRT are so small (±5 percent) that this capability may well be justified from a solids handling design redundancy standpoint, especially if low main stream CRT's are anticipated in design operation.

TABLE 13. DESIGN CRITERIA FOR OPTIMUM/COST-EFFECTIVE ACTIVATED SLUDGE SYSTEM (CRT = 7 DAYS)

Plant	Bissell Point	Lemay
Aerator (Average Day)		
MLSS - mg/l	5380	4280
D_t - Hrs.	3.9	2.4
SVI - $\frac{ml}{g}$	48	43
$\frac{lb\ COD/DAY}{lb\ MLVSS}$	0.74	0.73
$\frac{lb\ BOD/DAY}{lb\ MLVSS}$	0.34	0.37
Final Sedimentation (Average Day)		
D_t - Hrs. @ SWD = 12' SWD	2.9	1.8
Surface Overflow Rate - $\frac{gpd}{SF}$	750	1160
Return Sludge		
R_{ave} = mgd	23	15
R_{max} = mgd	32	22
Oxygen Supply		
Ave - tons/day	141	58
Max - tons/day	242	107

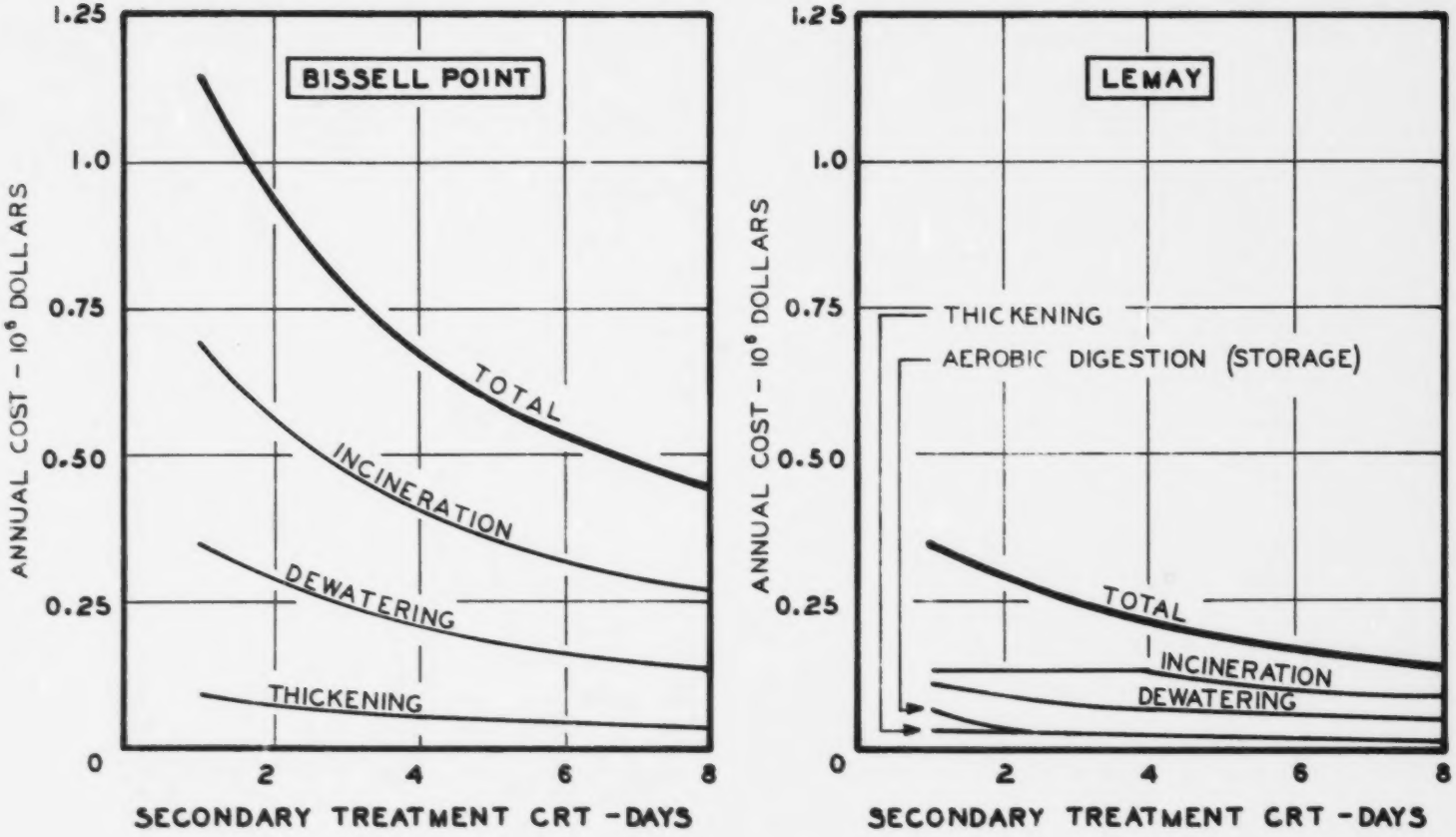


FIGURE 18. WASTE ACTIVATED SLUDGE HANDLING COSTS VS. SECONDARY TREATMENT

Figure 19 shows the total treatment costs of the secondary system as a function of the secondary treatment CRT. The high pollutant mass removals achieved at Bissell Point in comparison to the diluted Lemay wastewater and the resultant impact in the waste solids handling system are well demonstrated. The cost of waste solids handling in comparison to the total annual costs of the treatment system at Bissell Point range from 49 percent for a CRT of one day, to 15 percent for a CRT of 8 days (not including primary sludge). The percentage costs of waste sludge handling at Lemay are about one-half of those found at Bissell Point.

As mentioned previously, to assure operational flexibility, the design of a secondary activated sludge system is based on one CRT, and design of the waste sludge handling system at another. The highest value (CRT = 7 from Figure 13) is used for design of the components (aerator, sedimentation, oxygen supply, return sludge) of the main treatment system. The lowest value (CRT = 4) is used for design of the waste solids handling system. Figure 20 illustrates the percentage increase in the total annual expenditures by designing with this concept. Designing the waste solids handling sequence for a CRT of four days (the lower limit indicated from Figure 13) shows a percentage increase of only 5.5 percent at Bissell Point and 3.5 percent at Lemay. This is clearly a negligible expense when the increased design reliability and operational flexibility are considered.

CONCLUSIONS

Detailed cost-effective mathematical models were developed to describe design of a pure oxygen activated sludge system and handling of the resultant waste activated sludge for a pure oxygen activated sludge system. These models were tested using the input parameters established from diurnal plant investigations and a pure oxygen pilot plant study.

It was found that the optimum point of design reliability for secondary treatment was 97.6 percent, or a failure interval of four hours per week. Increasing reliabilities resulted in a gradual decline of the benefit/cost ratio to about 90 percent of optimum at a failure interval of four hours per six months (99.91 percent design reliability). The traditional operating tools (oxygen supply and return sludge capabilities) were relatively insensitive contributors to the annual costs of secondary treatment, having little bearing on the final optimized design. Optimum secondary treatment conditions were compared with conventional criteria and standards[11][12] with significant deviations only noted in terms of return sludge capabilities due to the superior densification characteristics of the pure oxygen sludges.

A waste activated sludge handling sequence incorporating gravity thickening, aerobic digestion (storage), vacuum filtration dewatering, and multiple-hearth incineration was examined. Gravity thickening was always found to be cost-effective. Aerobic digestion (storage)

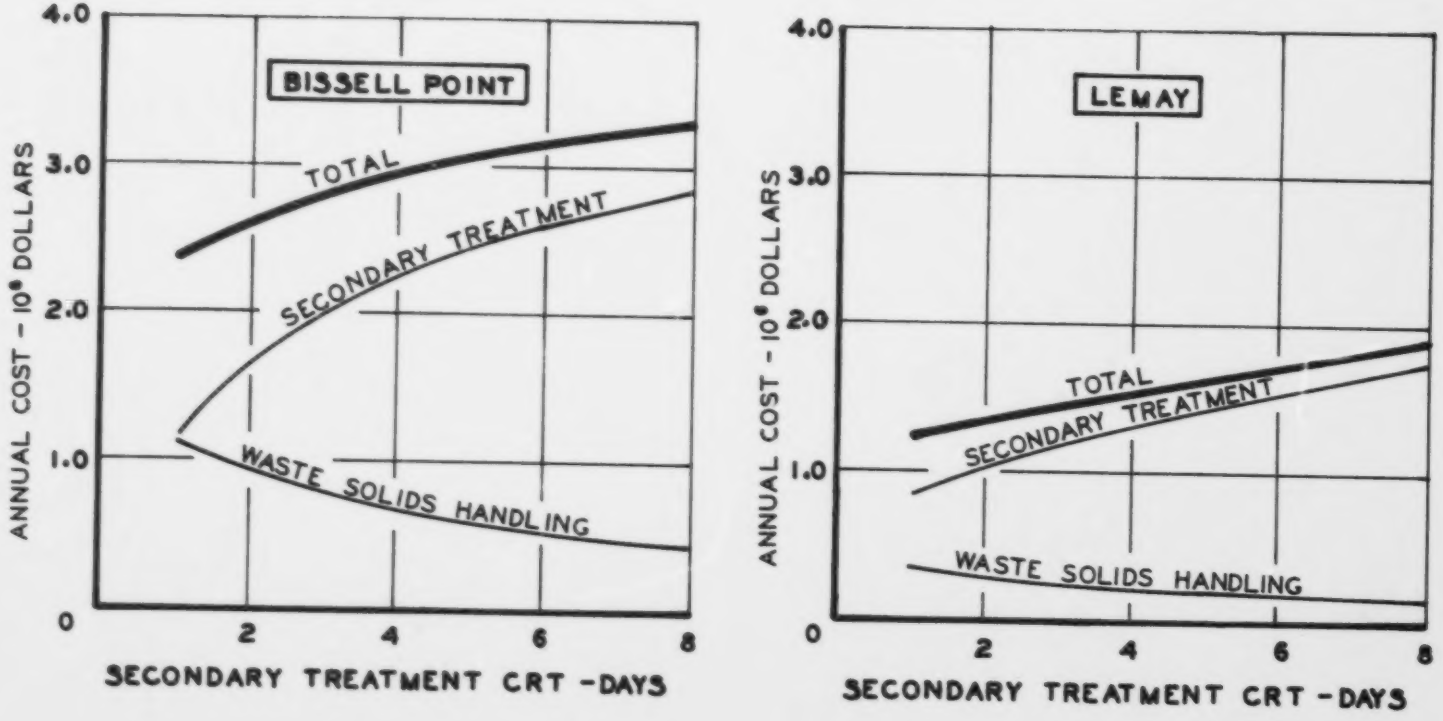


FIGURE 19. TOTAL ANNUAL TREATMENT EXPENDITURES VS. SECONDARY TREATMENT CRT

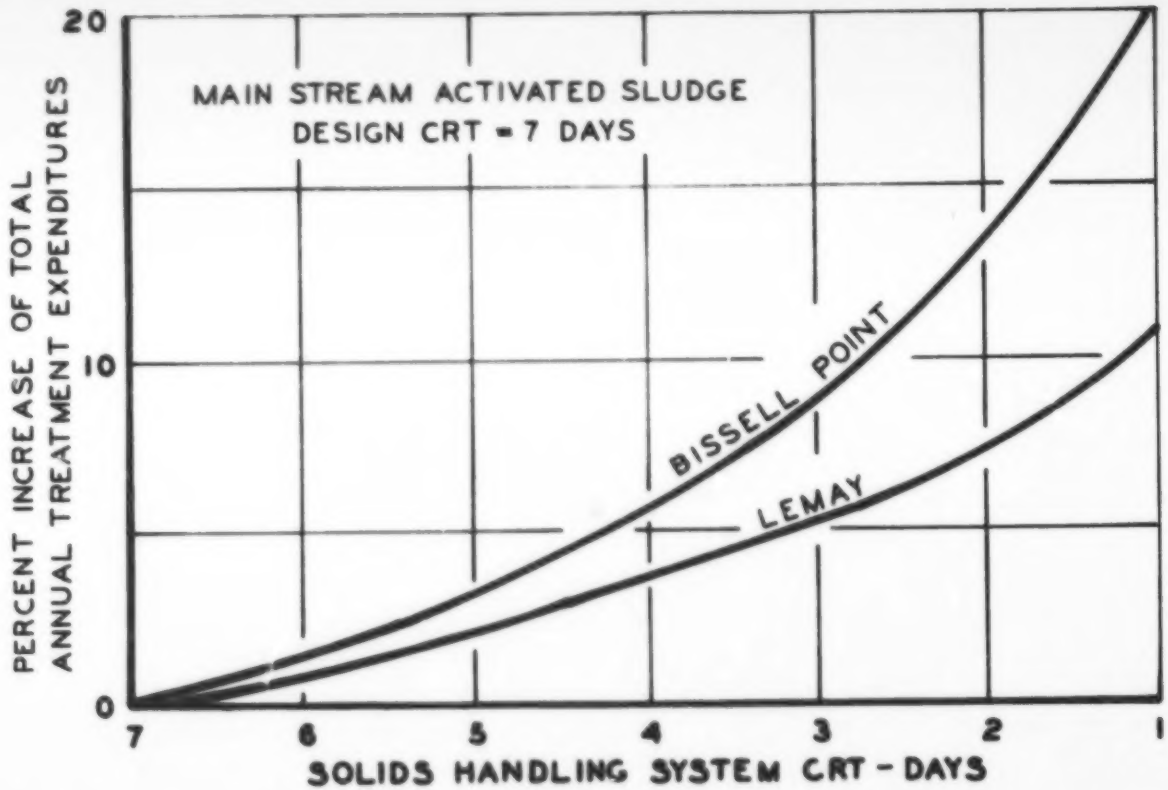


FIGURE 20. PERCENT INCREASE OF TOTAL ANNUAL TREATMENT EXPENDITURES VS. SOLIDS HANDLING SYSTEM CRT

was generally found to be not cost-effective for main system CRT's of 4 days or more. However, its cost liability when providing for one maximum day of storage was minimal at 5 percent or less of the total facility cost. Designing the waste solids handling sequence at a CRT of 4 days with a main stream activated sludge system design of 7 days was found to increase the total annual costs of the treatment complex by only 3.5 to 5.5 percent. This is clearly a negligible expense when the increased design reliability and operational flexibility are considered.

The models prepared herein and the conclusions obtained are believed valid for the pure oxygen activated sludge systems described. Although reasonable inferences may be drawn which would be useful in other applications, direct application of the data of this investigation to other types of treatment on different wastewaters should be avoided. Indeed, pure oxygen wastewater treatment is only one of many viable secondary treatment alternates under consideration for both the Lemay and Bissell Point treatment plants. Its use in this report has been merely for illustrative purposes to demonstrate the integration of pilot plant results into facility design.

SECTION VII

ACKNOWLEDGEMENTS

An investigation of this nature requires the conscientious contribution and cooperation of many individuals and organizations. We are most happy to acknowledge these efforts.

Mr. George Schillinger of the Metropolitan St. Louis Sewer District provided overall project coordination and supervised the collection and initial data reduction of all specially-conducted plant, pilot plant, and bench investigations. We are especially indebted for the efforts of his staff. Laboratory analyses during the pilot plant activities were performed by or under the supervision of Mr. Steve Friedman. The contributions of the Plant Superintendents (Messrs. John McCarthy at Bissell Point, and Roger Wieting at Lemay), Chief Chemists (Messrs. Charles Birkenkamper and Donald Renner), and Operators were fundamental to the project's success.

Mr. Peter Mattei, Executive Director, and Mr. Charles Kaiser, General Counsel, of MSD were instrumental in the development of the project and in arranging the many details of cooperation between Havens and Emerson and the District's staff. The support of the project by the Office of Research and Development of the U.S. Environmental Protection Agency and the guidance provided by Mr. Edwin Barth, Project Officer, are acknowledged with sincere appreciation.

In Havens and Emerson's Cleveland Office, the work was directed by Mr. George Simpson, Project Manager, and Mr. Michael Mulbarger, Director of Process Development. Mr. Pramod Khanna developed the computer programs.

SECTION VIII

REFERENCES

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12. "Sewage Treatment Plant Design," WPCF Manual of Practice No. 8 (1967).

SECTION IX

LIST OF PATENTS AND PUBLICATIONS

No publications or patents associated with the project have been produced or are pending as of this date of this report.

SECTION X

APPENDICES

		Page
A.	Diurnal - Frequency - Consecutive (DFC) Computer Program	69
B.	Activated Sludge (AS) Computer Program	82
C.	Waste Activated Sludge (WAS) Computer Program	87

APPENDIX A

DIURNAL - FREQUENCY - CONSECUTIVE (DFC) COMPUTER PROGRAM

To run the program DFC, in Statement No. 230, INFILE is replaced by the INPUT FILE NAME. The input file names for this study were BISDATIN and LEMDATIN for the Bissell Point and Lemay plants, respectively. A listing of the input files is as follows:

BISDATIN

```
100     'BISPOT', 'BISSELL'
110     'BPMRJN72'
120     'MARCH', 31
130     'APRIL', 30
140     'MAY', 31
150     'JUNE', 30
160     'YYY', 0
170     'BPJLOC72'
180     'JULY', 31
190     'AUGUST', 31
200     'SEPTEMBER', 30
210     'OCTOBER', 31
220     'YYY', 0
230     'XXX'
```

LEMDATIN

```
100     'LEMPOT', 'LEMAY'
110     'LEFBMY72'
120     'FEBRUARY', 29
130     'MARCH', 31
140     'APRIL', 30
150     'MAY', 31
160     'YYY', 0
170     'LEJNSP72'
180     'JUNE', 30
190     'JULY', 31
200     'AUGUST', 31
210     'SEPTEMBER', 30
220     'YYY', 30
230     'XXX'
```

'BPMRJN72', 'BPJLOC72', 'LEFBMY72', and 'LEJNSP72' were input files created before running the program. Each file contained four months of data, composed of flow, COD and SS measurements. These measurements were listed in terms of date, day of the week, average parameters for the day, and the measurement at 0030, 0430, 0830, 1230, 1630, and 2030 hours.

An extract of BPMRJN72, Bissell Point data for March, 1972 is given in the subsequent section.

```
100     1, 3, 116
110     110, 100, 150, 120, 120, 120
120     2, 4, 111
130     100, 90, 120, 120, 120, 120            March Flows
---
---
700     31, 5, 124
710     100, 80, 110, 120, 190, 140


720     1, 3, 538
730     749, 650, 716, 840, 864, 782
---                                            March COD
---
1320    31, 5, 500
1330    607, 884, 636, 583, 570, 547


1340    1, 3, 145.12
1350    148, 116, 126, 148, 151, 148
---                                            March SS
---
1940    31, 5, 107.55
1950    72, 397, 74, 54, 144, 116
```

Other files were similarly arranged. The complete DFC program is given on the following pages of this appendix.

```
100 FTAN: PROCEDURE;
110 DCL (MNF(12,10),MNC(12,10),MNS(12,10)) FIXED(7,2);
120 DCL (TUF(12,10),TUC(12,10),TUS(12,10)) FIXED(7,2);
130 DCL (WDF(12,10),WDC(12,10),WDS(12,10)) FIXED(7,2);
140 DCL (THF(12,10),THC(12,10),THS(12,10)) FIXED(7,2);
150 DCL (FRF(12,10),FRC(12,10),FRS(12,10)) FIXED(7,2);
160 DCL (SAF(12,10),SAC(12,10),SAS(12,10)) FIXED(7,2);
170 DCL (SUF(12,10),SUC(12,10),SUS(12,10)) FIXED(7,2);
180 DCL (TYF(12,10),TYC(12,10),TYS(12,10)) FIXED(7,2);
190 DCL (FLO(10,10),COD(10,10),SS(10,10)) FIXED(7,2);
200 DCL DATO FILE ENV(EXTERNAL) PRINT;
210 DCL (NAMI,NAMO) CHAR(8);
220 DCL NAMP CHAR(9);  DCL NAMM CHAR(9);
230 OPEN FILE(DATI) TITLE('INFILE') INPUT;
240 GET FILE(DATI) LIST(NAMO,N9);
250 Z9=0;
260 OPEN FILE(DATO) TITLE(NAMO) OUTPUT;
270 PUT FILE(DATO) LIST('IF YOUR DATA FILES CONTAIN ZEROES, THE CORRESP MIN RESULTS SHOULD BE IGNORED');
280 DECLARE NAME CHARACTER(8);
290 DECLARE NAMC CHARACTER(8);
300 DECLARE NAMS CHARACTER(8);
310 DECLARE (A(31,6),E(31,6)) FIXED(7,2);
320 DECLARE C(31,6);
330 DECLARE (B(31,3));
340  DECLARE (D(31,3));
350 DECLARE (G(31,6),T(31,6),U(31,6)) FIXED(7,2);
360 DCL (Q1,Q2,Q3,Q4,Q5) FIXED(7,2);
370 DCL (P(10,10),S(10,10)) FIXED (7,2);
380 DCL (T1,T2,T3,T4,T5) FIXED(7,2);
390 DECLARE V(10) CHARACTER(9);
400 DCL (R1,R2,R3,R4,R5,R6,R7,R8,R9) FIXED(7,2);
410 DECLARE (Q(31,3),R(31,3)) FIXED(7,2);
420 DCL (U1,U2,U3,U4,U5,U6,U7,U8,U9) FIXED(7,2);
430 DECLARE Y FIXED(7,2);
440 DECLARE (X,Z) FIXED(2);
450 IF Z9=1 THEN GOTO AGAIN;
```

```
460 LOOP: GET FILE(DATI) LIST(NAME);
470 IF NAME='XXX' THEN GOTO TABLE;
480 OPEN FILE(DATA) TITLE(NAME) INPUT;
490 AGAIN: Z9=Z9+1; X9=0;
500 IF N9=1 THEN GOTO IND;
510 GET FILE(DATI) LIST(NAMM,N);
520 IF NAMM='YYY' THEN GOTO KAKO;
530 CLOSE FILE(DATA); GOTO LOOP;
540 KAKO: GOTO START;
550 IND: GET FILE(DATI) LIST(NAMP,NAMM);
560 IF NAMP='XXX' THEN GOTO TABLE;
570 GET FILE(DATI) LIST(NAME,N); PUT FILE(DATO) SKIP;
580 OPEN FILE(DATA) TITLE(NAME) INPUT;
590 START: PUT FILE(DATO) SKIP(3);
600 PUT FILE(DATO) SKIP(3);
610 PUT FILE(DATO) LIST('                    ');
620 PUT FILE(DATO) LIST(NAMP);
630 PUT FILE(DATO) LIST('                ');
640 PUT FILE(DATO) LIST(NAMM);
650 PUT FILE(DATO) SKIP(5);
660 B=0; A=0; Q=0;
670 GET FILE(DATA) LIST((B(I,*),A(I,*) DO I=1 TO N));
680 IF N9=1 THEN CLOSE FILE(DATA);
690 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
700 DO I=1 TO N;
710 Q(I,1)=MAX(A(I,1),A(I,2),A(I,3),A(I,4),A(I,5),A(I,6));
720 Q(I,2)=MIN(A(I,1),A(I,2),A(I,3),A(I,4),A(I,5),A(I,6));
730 END;
740 PUT FILE(DATO) SKIP;
750 Q1=SUM(A); Q1=Q1/(N*6);
760 Q2=SUM(B(*,3));
770 Q2=Q2/N;
780 Q3=SUM(Q(*,1)); Q3=Q3/N;
790 Q3=Q3/Q1;
800 T3=SUM(Q(*,2)); T3=T3/N;
810 T1=Q1; T2=Q2;
```

```
820 T3=T3/T1;
830 V(1)='MONDAY'; V(2)='TUESDAY';
840 V(3)='WEDNESDAY'; V(4)='THURSDAY';
850 V(5)='FRIDAY'; V(6)='SATURDAY';
860 V(7)='SUNDAY'; V(8)='TYP  DAY';
870 PUT FILE(DATO) LIST('                    T Y P I C A L    W E E K  -  F L O W S   M G D');
880 PUT FILE(DATO) SKIP(5);
890 CALL TYPWK(B,A,Q);
900 Q4=S(5,1); Q4=Q4/Q1;
910 T4=S(5,2); T4=T4/T1;
920 Q5=Q(1,1); DO I=2 TO N;
930 Q5=MAX(Q5,Q(I,1)); END;
940 Q5=Q5/Q1;
950 T5=Q(1,2); DO I=2 TO N;
960 T5=MIN(T5,Q(I,2)); END;
970 T5=T5/T1;
980 PUT FILE(DATO) LIST('AV DIURNAL FLOW=  ', Q1, '   MGD');
990 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1000 PUT FILE(DATO) LIST('AV DLY PK FLOW= ', Q3, '  * AV DIURNAL'); PUT FILE(DATO) SKIP(2);
1010 PUT FILE(DATO) LIST('AV DLY MIN FLOW=', T3, '*AV DIURNAL');
1020 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1030 PUT FILE(DATO) LIST('AV WKLY PK FLOW= ', Q4, '  * AV DIURNAL'); PUT FILE(DATO) SKIP(2);
1040 PUT FILE(DATO) LIST('AV WKLY MIN FLOW=  ', T4, '   * AV DIURNAL');
1050 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1060 PUT FILE(DATO) LIST('MTHLY PEAK FLOW=  ', Q5, '  * AV DIURNAL');
1070 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1080 PUT FILE(DATO) LIST('MTHLY MIN FLOW=', T5, '*AV DIURNAL');
1090 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1100 PUT FILE(DATO) LIST('AV DLY FLOW=  ', Q2, '  MGD');
1110 PUT FILE(DATO) SKIP(3);
1120 X9=1; NAMC='COD';
1130 MORE: IF X9>2 THEN GOTO NOW;
1140 MNF(Z9,*)=FLO(1,*); TUF(Z9,*)=FLO(2,*);
1150 WDF(Z9,*)=FLO(3,*); THF(Z9,*)=FLO(4,*);
1160 FRF(Z9,*)=FLO(5,*); SAF(Z9,*)=FLO(6,*);
1170 SUF(Z9,*)=FLO(7,*); TYF(Z9,*)=FLO(8,*);
```

```
1180 MNC(Z9,*)=COD(1,*); TUC(Z9,*)=COD(2,*);
1190 WDC(Z9,*)=COD(3,*); THC(Z9,*)=COD(4,*);
1200 FRC(Z9,*)=COD(5,*); SAC(Z9,*)=COD(6,*);
1210 SUC(Z9,*)=COD(7,*); TYC(Z9,*)=COD(8,*);
1220 MNS(Z9,*)=SS(1,*); TUS(Z9,*)=SS(2,*);
1230 WDS(Z9,*)=SS(3,*); THS(Z9,*)=SS(4,*);
1240 FRS(Z9,*)=SS(5,*); SAS(Z9,*)=SS(6,*);
1250 SUS(Z9,*)=SS(7,*);  TYS(Z9,*)=SS(8,*);
1260 GOTO AGAIN;
1270 NOW: IF X9=2 THEN NAMC='SS';
1280 IF NAMC='SS' THEN DO;
1290 PUT FILE(DATO) LIST(' "DIURNAL" FIGURES ARE OF EFFLUENT        ');
1300 PUT FILE(DATO) LIST(' "DAY" FIGURES ARE OF REMOVAL');
1310 PUT FILE(DATO) SKIP(3); END;
1320 D=0; C=0; G=0; R=0;
1330 IF N9=0 THEN GOTO STO;
1340 GET FILE(DATI) LIST(NAMS); PUT FILE(DATO) SKIP(2);
1350 OPEN FILE(DATS) TITLE(NAMS) INPUT;
1360 GET FILE(DATS) LIST((D(I,*),C(I,*) DO I=1 TO N));
1370 GOTO ST1;
1380 STO: GET FILE(DATA) LIST((D(I,*),C(I,*) DO I=1 TO N));
1390 ST1: N8=N8;
1400 G=A*C*8.34/2000;
1410 DO I=1 TO N;
1420 R(I,1)=MAX(G(I,1),G(I,2),G(I,3),G(I,4),G(I,5),G(I,6));
1430 R(I,2)=MIN(G(I,1),G(I,2),G(I,3),G(I,4),G(I,5),G(I,6));
1440 IF NAMC='SS' THEN GOTO NONO;
1450 D(I,3)=B(I,3)*D(I,3)*8.34/2000;
1460 NONO: END;
1470 R2=SUM(D(*,3)); R2=R2/N;
1480 R1=SUM(G); R1=R1/(N*6);
1490 R3=(SUM(R(*,1)))/N;
1500 U1=R1; U2=R2;
1510 R3=R3/R1;
1520 U3=(SUM(R(*,2)))/N;
1530 U3=U3/U1;
```

```
1540 R5=R(1,1); DO I=2 TO N;
1550 R5=MAX(R5,R(I,1)); END;
1560 R5=R5/R1;
1570 U5=R(1,2); DO I=2 TO N;
1580 U5=MIN(U5,R(I,2)); END;
1590 U5=U5/U1;
1600 PUT FILE(DATO) LIST('                    T Y P I C A L    W E E K  -  ', NAMC, '  T O N S/D A Y');
1610 PUT FILE(DATO) SKIP(5);
1620 CALL TYPWK(D,G,R);
1630 R4=S(5,1); R4=R4/R1;
1640 U4=S(5,2); U4=U4/U1;
1650 PUT FILE(DATO) LIST('AV DIURNAL  ', NAMC,  R1, '  TONS/DAY');
1660 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1670 PUT FILE(DATO) LIST('AV DLY PK  ', NAMC, R3, '  * AV DIURNAL');
1680 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1690 PUT FILE(DATO) LIST('AV DLY MIN  ', NAMC,  U3,  '  * AV DIURNAL');
1700 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1710 PUT FILE(DATO) LIST('AV WKLY PK  ', NAMC,  R4,  '   *AV DIURNAL');
1720 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1730 PUT FILE(DATO) LIST('AV WKLY MIN', NAMC,U4, '*AV DIURNAL');
1740 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1750 PUT FILE(DATO) LIST('MTHLY PK  ', NAMC,  R5,  '  * AV DIURNAL');
1760 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
1770 PUT FILE(DATO) LIST('MTHLY MIN',NAMC,U5, '*AV DIURNAL');
1780 PUT FILE(DATO) SKIP(7);
1790 U6=D(1,3);
1800 R6=D(1,3); DO I=2 TO N;
1810 R6=MAX(R6,D(I,3));
1820 U6=MIN(U6,D(I,3)); END;
1830 R6=R6/R2; U6=U6/R2;
1840 X=1; Y=0; Z=N-2;
1850 Y3=D(1,3)+D(2,3)+D(3,3);
1860 DO I=1 TO Z;
1870 Y1=D(X,3)+D(X+1,3)+D(X+2,3);
1880 X=X+1;
1890 D(I,4)=Y1;
```

```
1900 IF Y1<Y THEN GOTO L2;
1910 Y=Y1;
1920 Y2=I;
1930 L2:IF Y1>Y3 THEN GOTO K2;
1940 Y3=Y1; Y4=I; K2:END;
1950 R7=Y/3; K7=Y2;
1960 R7=R7/R2;
1970 U7=Y3/3; M7=Y4; U7=U7/R2;
1980 X=1; Y=0; Z=N-4;
1990 Y3=D(1,3)+D(2,3)+D(3,3)+D(4,3)+D(5,3);
2000 DO I=1 TO Z;
2010 Y1=D(X,3)+D(X+1,3)+D(X+2,3)+D(X+3,3)+D(X+4,3);
2020 X=X+1;
2030 U(I,5)=Y1;
2040 IF Y1<Y THEN GOTO L3;
2050 Y=Y1;
2060 Y2=I;
2070 L3: IF Y1>Y3 THEN GOTO K3;
2080 Y3=Y1; Y4=I; K3: END;
2090 R8=Y/5; K8=Y2;
2100 R8=R8/R2;
2110 U8=Y3/5; M8=Y4; U8=U8/R2;
2120 X=1; Y=0; Z=N-6;
2130 Y3=D(1,3)+D(2,3)+D(3,3)+D(4,3)+D(5,3)+D(6,3)+D(7,3);
2140 DO I=1 TO Z;
2150 Y1=D(X,3)+D(X+1,3)+D(X+2,3)+D(X+3,3)+D(X+4,3)+D(X+5,3)+D(X+6,3);
2160 X=X+1;
2170 U(I,6)=Y1;
2180 IF Y1<Y THEN GOTO L4;
2190 Y=Y1;
2200 Y2=I;
2210 L4: IF Y1>Y3 THEN GOTO K4;
2220 Y3=Y1; Y4=I; K4:END;
2230 R9=Y/7; K9=Y2;
2240 R9=R9/R2;
2250 U9=Y3/7; M9=Y4; U9=U9/R2;
```

```
2260 PUT FILE(DATO) LIST('AV DAY   ', NAMC, R2, '   TONS/DAY');
2270 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2280 PUT FILE(DATO) LIST('MAX DAY  ', NAMC,  R6, '  * AV DAY');
2290 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2300 PUT FILE(DATO) LIST('MIN DAY  ', NAMC, U6, '  * AV DAY');
2310 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2320 PUT FILE(DATO) LIST('MAX 3 CONSEC DAY  ',  NAMC , R7,  '  * AV DAY');
2330 PUT FILE(DATO) LIST('     BEGINNING   ', K7, '  TH DAY');
2340 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2350 PUT FILE(DATO) LIST('MIN 3 CONSEC DAY  ', NAMC,  U7,  '  * AV DAY');
2360 PUT FILE(DATO) LIST('     BEGINNING   ', M7, '  TH DAY');
2370 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2380 PUT FILE(DATO) LIST('MAX 5 CONSEC DAY  ', NAMC,  R8, '  * AV DAY');
2390 PUT FILE(DATO) LIST('     BEGINNING   ', K8, '  TH DAY');
2400 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2410 PUT FILE(DATO) LIST('MIN 5 CONSEC DAY  ', NAMC,  U8, '  * AV DAY');
2420 PUT FILE(DATO) LIST('     BEGINNING   ', M8, '   TH DAY');
2430 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2440 PUT FILE(DATO) LIST('MAX 7 CONSEC DAY  ', NAMC,  R9, '  * AV DAY');
2450 PUT FILE(DATO) LIST('     BEGINNING   ', K9, '  TH DAY');
2460 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2470 PUT FILE(DATO) LIST('MIN 7 CONSEC DAY  ', NAMC, U9, '  * AV DAY');
2480 PUT FILE(DATO) LIST('     BEGINNING   ', M9, '  TH DAY');
2490 PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP; PUT FILE(DATO) SKIP;
2500 X9=X9+1;
2510 GOTO MORE;
2520 TYPWK: PROCEDURE(F,H,W);
2530 DECLARE (F(31,3));
2540 DCL W(31,3) FIXED(7,2);
2550 DECLARE H(31,6) FIXED(7,2);
2560 F1=F(1,2); F2=F(2,2);
2570 F3=F(3,2); F4=F(4,2);
2580 F5=F(5,2); F6=F(6,2);
2590 F7=F(7,2); X1=1;
2600 FNN: IF X1=1 THEN GOTO XX1;
2610 IF X1=2 THEN GOTO XX2;
```

```
2620 IF X1=3 THEN GOTO XX3;
2630 IF X1=4 THEN GOTO XX4;
2640 IF X1=5 THEN GOTO XX5;
2650 IF X1=6 THEN GOTO XX6;
2660 IF X1=7 THEN GOTO XX7;
2670 IF X1>7 THEN GOTO FHL;
2680 XX1: J=F1; IF N=28 THEN GOTO X4X; GOTO X5X;
2690 XX2: J=F2; IF N.29 THEN GOTO X4X; GOTO X5X;
2700 XX3: J=F3; IF N.30 THEN GOTO X4X; GOTO X5X;
2710 XX4: J=F4; GOTO X4X;
2720 XX5: J=F5; GOTO X4X;
2730 XX6: J=F6; GOTO X4X;
2740 XX7: J=F7; GOTO X4X;
2750 X4X: DO I=1 TO 6;
2760 P(J,I)=(H(X1,I)+H(X1+7,I)+H(X1+14,I)+H(X1+21,I))/4;
2770 END; GOTO FHM;
2780 X5X: DO I=1 TO 6;
2790 P(J,I)=(H(X1,I)+H(X1+7,I)+H(X1+14,I)+H(X1+21,I)+H(X1+28,I))/5;
2800 END; GOTO FHM;
2810 FHM: X1=X1+1; IF X1>7 THEN GOTO FHL; GOTO FHN;
2820 FHL: DO J=1 TO 7;
2830 P(J,7)=MAX(P(J,1),P(J,2),P(J,3),P(J,4),P(J,5),P(J,6));
2840 P(J,8)=MIN(P(J,1),P(J,2),P(J,3),P(J,4),P(J,5),P(J,6));
2850 P(J,9)=P(J,1)+P(J,2)+P(J,3)+P(J,4)+P(J,5)+P(J,6);
2860 P(J,9)=(P(J,9))/6;
2870 END;
2880 DO I=1 TO 9;
2890 P(8,I)=P(1,I)+P(2,I)+P(3,I)+P(4,I)+P(5,I)+P(6,I)+P(7,I);
2900 P(8,I)=(P(8,I))/7;
2910 END;
2920 IF X9=0 THEN FLO- ;
2930 IF X9=1 THEN COD=P;
2940 IF X9=2 THEN SS=P;
2950 PUT FILE(DATO) SKIP(3);
2960 PUT FILE(DATO) LIST('   D A Y        0030        0430        0830        1230        1630        2030');
2970 PUT FILE(DATO) LIST('          MAX         MIN         AVG');
```

```
2980 PUT FILE(DATO) SKIP(3);
2990 DO J=1 TO 8;
3000 PUT FILE(DATO) EDIT(V(J),(P(J,I) DO I=1 TO 9))
3010 (A(9),X(5),F(6,2),X(5),F(6,2),X(5),F(6,2),X(5),F(6,2),X(5),F(6,2),X(5),F(6,2),
3020 X(7),F(6,2),X(5),F(6,2),X(5),F(6,2));
3030 PUT FILE(DATO) SKIP(2); END;
3040 S(1,1)=MAX(W(1,1),W(2,1),W(3,1),W(4,1),W(5,1),W(6,1),W(7,1));
3050 S(1,2)=MIN(W(1,2),W(2,2),W(3,2),W(4,2),W(5,2),W(6,2),W(7,2));
3060 S(2,1)=MAX(W(8,1),W(9,1),W(10,1),W(11,1),W(12,1),W(13,1),W(14,1));
3070 S(2,2)=MIN(W(8,2),W(9,2),W(10,2),W(11,2),W(12,2),W(13,2),W(14,2));
3080 S(3,1)=MAX(W(15,1),W(16,1),W(17,1),W(18,1),W(19,1),W(20,1),W(21,1));
3090 S(3,2)=MIN(W(15,2),W(16,2),W(17,2),W(18,2),W(19,2),W(20,2),W(21,2));
3100 S(4,1)=MAX(W(22,1),W(23,1),W(24,1),W(25,1),W(26,1),W(27,1),W(28,1));
3110 S(4,2)=MIN(W(22,2),W(23,2),W(24,2),W(25,2),W(26,2),W(27,2),W(28,2));
3120 S(5,1)=S(1,1)+S(2,1)+S(3,1)+S(4,1);
3130 S(5,1)=(S(5,1))/4;
3140 S(5,2)=S(1,2)+S(2,2)+S(3,2)+S(4,2);
3150 S(5,2)=(S(5,2))/4;
3160 PUT FILE(DATO) SKIP(2);
3170 END TYPWK;
3180 TABLE: N2=0;
3190 PUT FILE(DATO) LIST('                    MONDAY FLOWS');
3200 CALL TP(MNF);
3210 PUT FILE(DATO) LIST('                    TUESDAY FLOWS');
3220 CALL TP(TUF);
3230 PUT FILE(DATO) LIST('                    WEDNESDAY FLOWS');
3240 CALL TP(WDF);
3250 PUT FILE(DATO) LIST('                    THURSDAY FLOWS');
3260 CALL TP(THF);
3270 PUT FILE(DATO) LIST('                    FRIDAY FLOWS');
3280 CALL TP(FRF);
3290 PUT FILE(DATO) LIST('                    SATURDAY FLOWS');
3300 CALL TP(SAF);
3310 PUT FILE(DATO) LIST('                    SUNDAY FLOWS');
3320 CALL TP(SUF);
3330 PUT FILE(DATO) LIST('                    TYPICAL DAY FLOWS');
```

```
3340 CALL TP(TYF);
3350 PUT FILE(DATO) LIST('                    MONDAY COD');
3360 CALL TP(MNC);
3370 PUT FILE(DATO) LIST('                    TUESDAY COD');
3380 CALL TP(TUC);
3390 PUT FILE(DATO) LIST('                    WEDNESDAY COD');
3400 CALL TP(WDC);
3410 PUT FILE(DATO) LIST('                    THURSDAY COD');
3420 CALL TP(THC);
3430 PUT FILE(DATO) LIST('                    FRIDAY COD');
3440 CALL TP(FRC);
3450 PUT FILE(DATO) LIST('                    SATURDAY COD');
3460 CALL TP(SAC);
3470 PUT FILE(DATO) LIST('                    SUNDAY COD');
3480 CALL TP(SUC);
3490 PUT FILE(DATO) LIST('                    TYPICAL DAY COD');
3500 CALL TP(TYC);
3510 PUT FILE(DATO) LIST('                    MONDAY SUSP SOLIDS EFFLUENT');
3520 CALL TP(MNS);
3530 PUT FILE(DATO) LIST('                    TUESDAY SUSP SOLIDS EFFLUENT');
3540 CALL TP(TUS);
3550 PUT FILE(DATO) LIST('                    WEDNESDAY SUSP SOLIDS EFFLUENT');
3560 CALL TP(WDS);
3570 PUT FILE(DATO) LIST('                    THURSDAY SUSP SOLIDS EFFLUENT');
3580 CALL TP(THS);
3590 PUT FILE(DATO) LIST('                    FRIDAY SUSP SOLIDS EFFLUENT');
3600 CALL TP(FRS);
3610 PUT FILE(DATO) LIST('                    SATURDAY SUSP SOLIDS EFFLUENT');
3620 CALL TP(SAS);
3630 PUT FILE(DATO) LIST('                    SUNDAY SUSP SOLIDS EFFLUENT');
3640 CALL TP(SUS);
3650 PUT FILE(DATO) LIST('                    TYPICAL DAY SUSP SOLIDS EFFLUENT');
3660 CALL TP(TYS);
3670 GOTO LESS;
3680 TP: PROCEDURE(TD);
3690 DCL MTH(15) CHAR(9);
```

```
3700 DCL TD(15,9) FIXED(7,2);
3710 MTH(1)='FEBRUARY'; MTH(2)='MARCH';
3720 MTH(3)='APRIL'; MTH(4)='MAY';
3730 MTH(5)='JUNE'; MTH(6)='JULY';
3740 MTH(7)='AUGUST'; MTH(8)='SEPTEMBER';
3750 MTH(9)='AVERAGE';
3760 MTH(10)='MAXIMUM'; MTH(11)='MINIMUM';
3770 DO I=1 TO 6;
3780 TD(9,I)=TD(1,I)+TD(2,I)+TD(3,I)+TD(4,I)+TD(5,I)+TD(6,I)+TD(7,I)+TD(8,I);
3790 TD(9,I)=(TD(9,I))/8;
3800 TD(10,I)=MAX(TD(1,I),TD(2,I),TD(3,I),TD(4,I),TD(5,I),TD(6,I),TD(7,I),TD(8,I));
3810 TD(11,I)=MIN(TD(1,I),TD(2,I),TD(3,I),TD(4,I),TD(5,I),TD(6,I),TD(7,I),TD(8,I));
3820 END;
3830 PUT FILE(DATO) SKIP(2);
3840 PUT FILE(DATO) LIST('M O N T H       0030       0430       0830       1230       1630       2030');
3850 PUT FILE(DATO) SKIP(3);
3860 DO J=1 TO 11;
3870 PUT FILE(DATO) EDIT(MTH(J),(TD(J,I) DO I=1 TO 6))
3880 (A(9),X(5),F(6,2),X(5),F(6,2),X(5),F(6,2),X(5),F(6,2),X(5),F(6,2),X(5),F(6,2));
3890 PUT FILE(DATO) SKIP(2); END;
3900 PUT FILE(DATO) SKIP(5);
3910 END TP;
3920 LESS: N2=0;
3930 END FTAN;
```

APPENDIX B

ACTIVATED SLUDGE (AS) COMPUTER PROGRAM

The AS program is listed on the following pages of this Appendix.

```
1000 PRINT "RUN NO?"
1020 PRINT
1040 PRINT
1060 INPUT S$
1080 PRINT
1100 PRINT
1120:  ##.##   ######.   ########.   ########.   ########.   #########.   #########.   ########.
1140:  ##.##   ######.   ########.   ########.   ########.   #########.   #########.   ########.
1150 PRINT "DO YOU WISH TO PRINT SYMBOL EXPLANATIONS? YES/NO"
1180 INPUT A$
1200 IF A$='NO' GOTO 1900
1220 PRINT "CELL RESIDENCE TIME DAYS = C"
1240 PRINT "ENDOGENOUS DECAY COEFF = K"
1260 PRINT "SUBSTRATE REMOVED MG/L = X"
1280 PRINT "CELL YIELD = Y"
1300 PRINT "FLOW MGD = Q"
1320 PRINT "EFFLUENT DO = E"
1340 PRINT "OXYGEN PEAK FACTOR = P1"
1360 PRINT "EFFICIENCY OF OXYGEN TRANSFER = G"
1380 PRINT "COD BALANCE ADJ FACTOR = K1"
1400 PRINT "HYDRAULIC PEAK FACTOR = P2"
1420 PRINT "TEMP/PHYS ADJ FACTOR = K4"
1440 PRINT "CONCENTRATION FACTOR = F"
1460 PRINT "SVI COEFF =  H1"
1480 PRINT "SVI EXPONENT =  H2"
1500 PRINT "WAS COD/VS RATIO = B"
1520 PRINT "INFLUENT INERT SUSP SOLIDS = S1"
1540 PRINT "SETTLING RATE GPD/SFT  =  F1(10↑6)/(MLSS)↑F2"
1560 PRINT "SVI= H1(E)↑(A.H2)"
1580 PRINT "A1 = $/MCF OF TANK VOLUME"
1600 PRINT "B1 = $/MSF OF SURFACE AREA"
1620 PRINT "C1 = $/MGD OF RETURN SLUDGE"
1640 PRINT "D1 = $/TON/DAY OF OXYGEN"
1660 PRINT "DETENTION TIME HOURS = T"
1680 PRINT "AERATION TIME ADJUSTMENT FACTOR = K2 = 1.28-0.078T+0.003T↑2"
1700 PRINT "OXYGEN REQD MG/L= X(1-BY/(1+CK))(K1/G)G1.K2"
```

```
1720 PRINT "NET VOL SOLIDS PRODUCTION = L1 = X.Y/(1+C.K)"
1740 PRINT "VOL MLS = L = C.L1"
1760 PRINT "TOTAL MIXED LIQUOR SUSP SOLIDS= C(S1+XY/(1+CK)"
1780 PRINT "DO YOU WANT TO RUN PROGRAM? YES/NO"
1800 INPUT D$
1820 IF D$= 'NO' GOTO 10000
1840 PRINT
1860 PRINT
1880 PRINT
1900 PRINT "INPUT C,K,X,Y,Q"
1920 INPUT C,K,X,Y,Q
1940 PRINT "INPUT E,P1,G,K1"
1960 INPUT E,P1,G,K1
1980 PRINT "INPUT P2,K4,F,H1,H2"
2000 INPUT P2,K4,F,H1,H2
2020 PRINT "INPUT B,S1,F1,F2"
2040 INPUT B,S1,F1,F2
2060 IF Z1=1 GOTO 2120
2080 PRINT "INPUT A1,B1,C1,D1"
2100 INPUT A1,B1,C1,D1
2120 R1=10**10
2140 L1 = (X*Y)/(1+(C*K))
2160 L2=L1+S1
2180 L=C*L2
2200 M=24*L
2220 S1=F1*(10**6)/(M**F2)
2240 S=S1*K4
2260 A7=1000*P2/S
2280 U=X*(1-(B*Y/(1+C*K)))*K1/G
2300 U1=0.069*Q*U
2320 U2=U1*0.061
2340 PRINT
2360 PRINT "NET VOL SOLIDS PROD = ",L1,"/DAY"
2380 PRINT "TOTAL MIXED LIQUOR SUSP SOLIDS =L=",L,"MG/L"
2400 PRINT "MLSS = ",M;"   /T"
2420 PRINT "SETTLING RATE GPD/SFT = S*(T↑F2)/P2 WHERE S=",S
```

```
2440 PRINT "OXYGEN REQD MG/L = U.G1.K2 WHERE U = ",U
2460 T4=M/10000
2480 T5=M/4000
2500 PRINT
2520 PRINT "T MIN = ", T4, "HOURS"
2540 PRINT "T MAX = ",T5,"HOURS"
2560 PRINT
2580 PRINT
2600 PRINT "SELECT T1>T MIN AND T2<TMAX AND STEP T3"
2620 PRINT "IF ONLY OPTIMAL VALUES ARE TO BE PRINTED INPUT Z4 = 0"
2640 PRINT "INPUT T1,T2,T3,Z4"
2660 INPUT T1,T2,T3,Z4
2680 PRINT
2700 PRINT
2720 PRINT "   T      MLSS     AERATION    SETTLING    RTN PUMP    OXY PROD    TOTAL COST    COST $/MGD"
2740 PRINT
2760 FOR T = T1 TO T2 STEP T3
2780 A = M/T
2800 X1=H1*(&E)**((A)*H2)
2820 K3=F*(10**6)/X1
2840 H4=(K3/A)-1
2860 H5=P2/H4
2880 K2=1.28-0.078*T+0.003*T**2
2900 K2=K2*P1
2920 A2=5.57*A1*T
2940 A3=A2*Q
2960 B2=A7*D1/(T**F2)
2980 B3=B2*Q
3000 C2 = C1*H5
3020 C3=C2*Q
3040 D2=D1*0.0042*K2*U
3060 D3=D2*Q
3080 W1=A2+B2+C2+D2
3100 W = W1*Q
3120 IF Z4=0 GOTO 3240
3140 PRINT USING 1120 , T,A,A3,B3,C3,D3,W,W1
```

```
3160 PRINT
3180 IF W>R1 GOTO 3320
3200 PRINT "**"
3220 PRINT
3240 IF W>R1 GOTO 3320
3260 R1=W
3280 W9=W1
3300 GOSUB 3620
3320 NEXT T
3340 PRINT
3360 PRINT USING 1120 , T9,M9,A9,B9,C9,D9,R1,W9
3380 PRINT "****"
3400 PRINT
3420 PRINT "IF YOU WANT TO TRY OTHER VALUES OF T"
3440 PRINT "INPUT Z2 = 1, OTHERWISE Z2 = 0"
3460 INPUT Z2
3480 IF Z2=1 GOTO 2640
3500 X1=M1*(EE)**((M9)*H2)
3520 K3=F*(10**6)/X1
3540 PRINT
3560 PRINT "SVI AT OPT  T  =  ",K3
3580 PRINT
3600 IF Z1=0 GOTO 10000
3620 T9=T
3640 M9=A
3660 A9=A3
3680 B9=B3
3700 C9=C3
3720 D9=D3
3740 Q9=Q
3760 RETURN
10000 END
```

APPENDIX C

WASTE ACTIVATED SLUDGE (WAS) COMPUTER PROGRAM

The WAS program is listed on the following pages of this Appendix.

```
1700 PRINT "INCINERATION COST $/SFT HEARTH=V7"
1720 PRINT
1740 PRINT "CELL RESIDENCE TIME (OVERALL SYSTEM) DAYS=C0"
1760 PRINT
1780 PRINT "K5=1 FOR C0=0 TO 10"
1800 PRINT "K5=1.05 FOR C0=10-15, K5=1.10 FOR C0=15 TO 20"
1820 PRINT "K5=1.15 FOR C0=15-20, K5=1.20 FOR C0=25 TO 30"
1840 PRINT "WASTE VOLATILE SOLIDS = L1 = XY/(1+CK)"
1860 PRINT "WASTE SOLIDS = L2 = L1+S1"
1880 PRINT "WASTE ACTIVATED SLUDGE = L3 = (L2-S2)P3"
1900 PRINT "WASTE ACTIVATED VOLATILE SLUDGE = L4 = L1(1-S2/L2)P3"
1920 PRINT "WASTE ACTIVATED INERT SLUDGE = L5 = L3-L4"
1940 PRINT "WASTE VOLATILE SOLIDS RESIDUAL = L6 = XY/(1+C0.K)"
1960 PRINT "WASTE ACTIVATED VOLATILE SOLIDS RESIDUAL = L7 = L4.L6/L1"
1980 PRINT "WAVSR ADJUSTED = L8 = K5.L7.P4/P3"
2000 PRINT "THICKENED SLUDGE FLOW MGD = L9 = Q.L3/C1"
2020 PRINT "VOLUME AEROBIC DIGESTER MG = K3= L9(C0-C)P4.10↑6/7.48P3"
2040 PRINT "OXYGEN REQD TONS/DAY = 8.34.Q.8(L4-L8)K1/2000G"
2060 PRINT "THICKENER SURFACE AREA SFT = 8.34.Q.L3/T1"
2080 PRINT "THICKENED SLUDGE FLOW MGD = Q.L3/C1"
2100 PRINT "CONC OF AEROBICALLY DIGESTED SOLIDS % = C1(L8+L5.P4/P3)/L3.10↑4"
2120 PRINT "DEWATERING SURFACE AREA SFT = G6 = 8.34Q.K6.L3.10↑4/C1.H3"
2140 PRINT "TOTAL WET SOLIDS/HR=M5=8.34Q(L8+L5.P4/P3)K6"
2160 PRINT "INCINERATION SURFACE AREA SFT = M6 = M5/(C3.H3.11)"
2180 PRINT
2200 PRINT "DO YOU WANT TO RUN PROGRAM? YES/NO"
2220 INPUT D$
2240 IF D$='NO' GOTO 10000
2260 PRINT "INPUT C,X,Y"
2280 INPUT C,X,Y
2300 PRINT "INPUT K,S1,S2,Q"
2320 INPUT K,S1,S2,Q
2340 PRINT "INPUT P3,T1,C1,G,K6"
2360 INPUT P3,T1,C1,G,K6
2380 PRINT "INPUT M1,M2,H3,C3"
2400 INPUT M1.M2.H3.C3
```

```
2420 PRINT "INPUT I1,K1,B"
2440 INPUT I1,K1,B
2460 PRINT "INPUT D1,V4,V5,V6,V7"
2480 INPUT D1,V4,V5,V6,V7
2500 R1=10**10
2520 L1=(X*Y)/(1+C*K)
2540 L2=L1+S1
2560 L3=(L2-S2)*P3
2580 L4=L1*(1-(S2/L2))*P3
2600 L5=L3-L4
2620 PRINT
2640 PRINT
2660 PRINT "SELECT V1≥";C;" AND V2≤15+",C,"  AND STEP V3 AND PRINT OPTION Z4"
2680 PRINT "IF ONLY OPTIMAL VALUES ARE TO BE PRINTED Z4=0"
2700 PRINT "INPUT V1,V2,V3,Z4"
2720 INPUT V1,V2,V3,Z4
2740 PRINT
2760 PRINT
2780 PRINT "CO    OXY PROD    DIGESTON    THIKNING    DEWATRNG    INCINERN    TOTAL COST    $/MGD"
2800 PRINT
2820 FOR C0=V1 TO V2 STEP V3
2840 IF K5>0 GOTO 3140
2860 IF C0≤10 GOTO 3100
2880 IF C0≤15 GOTO 3060
2900 IF C0≤20 GOTO 3020
2920 IF C0≤25 GOTO 2980
2940 K5=1.20
2960 GOTO 3140
2980 K5=1.15
3000 GOTO 3140
3020 K5=1.10
3040 GOTO 3140
3060 K5=1.05
3080 GOTO 3140
3100 K5=1.00
3120 GOTO 3140
```

```
3140 L6=X*Y/(1+C0*K)
3160 IF C0≤C GOTO 3220
3180 P4=M1*((C0-C)**(M2))
3200 GOTO 3240
3220 P4=P3
3240 L6=X*Y/(1+C0*K)
3260 L7=L4*L6/L1
3280 L8=K5*L7*P4/P3
3300 L9=Q*L3/C1
3320 K3=(10**6)*L9*(C0-C)*P4/(P3*7.48)
3340 E8=K3*V4
3360 U4=(L4-L8)*K1*B/G
3380 D8=8.34*Q*U4*D1/2000
3400 E1=8.34*Q*L3/T1
3420 F8=E1*V5
3440 G6=(8.34*Q*K6*L3*10↑4)/(C1*H3)
3460 G8=G6*V6
3480 M5=(L8+L5*P4/P3)*Q*8.34*K6
3500 M6=M5/(C3*H3*I1)
3520 H8=M6*V7
3540 W=E8+D8+F8+G8+H8
3560 W1=W/Q
3580 IF Z4=0 GOTO 3700
3600 PRINT USING 1020, C0,D8,E8,F8,G8,H8,W,W1
3620 PRINT
3640 IF W>R1 GOTO 3920
3660 PRINT "*"
3680 PRINT
3700 IF W>R1 GOTO 3920
3720 R1=W
3740 W9=W
3760 Z9=W1
3780 E9=E8
3800 D9=D8
3820 F9=F8
3840 G9=G8
```

```
3860 H9=H8
3880 V9=C0
3900 U9=K3
3920 NEXT C0
3940 PRINT
3960 PRINT USING 1020, V9,D9,E9,F9,G9,H9,W9,Z9
3980 PRINT "######"
4000 PRINT
4020 PRINT "VOLUME OF AEROBIC DIGESTER (AT OPTIMUM)=",U9,"CFT"
4040 PRINT
4060 PRINT
4080 PRINT "MORE C0? YES=1 NO=0"
4100 INPUT Z2
4120 IF Z2=1 GOTO 2700
10000 END
```